91602
new 82-10

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if Reproduced in Whole or in Part.

ontario hydro
research division

EXECUTIVE SUMMARY

SIMULATED EARTHQUAKE TESTING OF NATURALLY AGED C&D LCU-13 STATION BATTERY CELLS

J.D. Tulk
Mechanical Research Department

D.A. Black
Mechanical Research Department

W.J. Janis
Chemical Research Department

C.J. Royce
Electrical Design Department

A sample of 10-year-old lead-acid storage batteries from the North Anna Nuclear Power Station (Virginia Electric and Power Company) were tested on a shaker table. Seven cells were subjected to simulated earthquakes with a ZPA of approximately 1.5 g. All seven delivered uninterrupted power during the shaker tests and were able to pass a post-seismic capacity test. Two cells were shaken to higher intensities (ZPA approximately equal to 2 g). These cells provided uninterrupted power during the shaker tests, but had post-seismic capacities that were below the required level for Class 1E battery cells. After the tests, several cells were disassembled and examined. Internal components were in good condition with limited oxidization and plate cracking.

JC

job	file	date	report no.
740621-108-450	825.92	March 1, 1985	85-48-K

TABLE OF CONTENTS

		Page
1.0	INTRODUCTION	1
2.0	TEST METHODS AND RESULTS	2
	2.1 Initial Inspection and Conditioning	2
	2.2 Seismic Testing - Single Cells	2
	2.3 Jar Fragility Test	4
	2.4 Multi-Cell Rack Test	4
	2.5 Post Seismic Capacity Tests and Inspection	5
3.0	CONCLUSIONS	5
4.0	ACKNOWLEDGEMENTS	6
	REFERENCES	7
	TABLES AND FIGURES	8
	DISTRIBUTION	last page

91600
new 82-10

ontario hydro
research division

To Mr. B.A. Oliver
Manager
Electrical Design Department

SIMULATED EARTHQUAKE TESTING OF NATURALLY AGED C&D LCU13 STATION BATTERY CELLS

A sample of 10-year-old lead-acid storage batteries from the North Anna Nuclear Power Station (Virginia Electric and Power Company) were tested on a shaker table. Seven cells were subjected to simulated earthquakes with a ZPA of approximately 1.5 g. All seven delivered uninterrupted power during the shaker tests and were able to pass a post-seismic capacity test. Two cells were shaken to higher intensities (ZPA approximately equal to 2 g). These cells provided uninterrupted power during the shaker tests, but had post-seismic capacities that were below the required level for Class 1E battery cells. After the tests, several cells were disassembled and examined. Internal components were in good condition with limited oxidization and plate cracking.

1.0 INTRODUCTION

The large lead-acid storage battery cells that are the subject of this report are used to provide DC power for nuclear power stations under emergency conditions. It is well known that these cells deteriorate with age and it is normal practice to test them at regular intervals to ensure that they are capable of meeting a specified level of performance. What is not so well understood however, is the effect of age on the mechanical fragility of the cells and whether the cells would be capable of surviving seismic events at the operating basis earthquake (OBE) or safe shutdown earthquake (SSE) levels and to continue to meet the load profile required by the Class 1E system. Because of the importance of storage batteries to the Class 1E system, the US Nuclear Regulatory Commission has requested Sandia National Laboratories (SNL) to evaluate the impact of aging and seismic exposure on battery capacity. Ontario Hydro has been subcontracted to carry out capacity and seismic shaker tests on naturally aged cells supplied by SNL from several US nuclear

job	file	date	report no.
740621-108-450	825.92	March 1, 1985	85-48-K

power stations (SNL contract 47-4077). The program addresses possible variations between designs produced by different manufacturers.

This report describes the results of a series of experiments carried out at the Ontario Hydro Research Laboratories on a set of ten (10) year old C&D LCU-13 cells from the North Anna Nuclear Power Station (Virginia Electric and Power Company). The tests showed that the cells were capable of withstanding simulated earthquakes with ZPA levels of about 1.5 g without a significant loss of capacity. When a small sample of cells was subjected to high intensity shaking (ZPA about 2 g) the cells were able to deliver uninterrupted power during the shaker tests, but showed significant losses in storage capacity. To determine if there was any age related deterioration of the internal components of the cells that did not manifest itself during the shaker tests, several cells were disassembled for inspection and metallurgical examination. The results indicate that this batch of cell was in good condition.

This report provides a summary of the test methods and results. More detailed discussions of the tests and results are contained in references 1, 2 (battery condition and performance), and 3 and 4 (seismic test results).

The tests described here were part of a larger program of testing of aged cells. Other cell types tested to date have included Gould FKR (Pickering NGS)/5,6,7/, Gould NCX2250 (J.A. Fitzpatrick NPS)/8/, Exide EMP-13 (Shippingport NPS)/9/ and Exide FHC-19 (Calvert Cliffs NPS)/10/.

2.0 TEST METHODS AND RESULTS

2.1 Initial Inspection and Conditioning

Twelve C&D LCU-13 cells were received from the North Anna plant. Once inspected for superficial damage (there was none), the cells were conditioned (charged and discharged several times to stabilize their condition) and tested for capacity. The electrical state of the cells prior to the seismic tests is summarized in Table 1.

2.2 Seismic Tests - Single Cells

The shaker table and instrumentation used in these experiments is described in Reference 3. The table provides independent motion in three directions. The motion is based on a quasi-random signal, filtered to match the frequency content of a

typical earthquake. The duration of each test was 30 s. The seismic test method was based on the recommendations of IEEE Std 344-1975 and IEEE Std 501-1978.

For the single cell seismic tests, the cells were mounted individually on the shaker table in a stiff frame, designed to minimize relative motion between the cell jar and the table (see Figure 1). These tests were intended to investigate possible failure modes of internal components. The rig was designed to minimize the danger of jar failure and acid spill. Accelerometers were mounted on the base of the frame and on the top of one of the posts of the cell.

During the seismic tests, the cells were discharged against a resistive load at a 1 hr discharge rate. They were considered to have "passed" a seismic test if they remained above 1.75 V during and immediately after the test. The cells were shaken at progressively higher levels up to the machine limit. Each of the four cells that were tested in the single cell frame passed all of the tests. Table 2 provides a log of the test sequence, while Table 3 summarizes the results. There were no sudden drops in cell voltage during any of the shaker tests.

Seismic test results are presented in this report and in References 3 and 4 in terms of acceleration response spectra of the table motion. To provide a convenient means of comparing the acceleration levels encountered during various tests, each test spectrum is compared to a normalized spectrum defined in IEEE Std 501-1978/11/. The shape of this spectrum is intended to reflect the frequency content of the "typical" seismic environment for electrical equipment. The intensity of the simulated seismic motion is expressed in terms of the ZPA (zero period acceleration) which provides a conservative lower-bound estimate of the peak acceleration of the base.

The single cell tests were conducted in two stages. In the first stage, the shaker table controllers were tuned so that the frequency content of the table motion fitted the standard spectrum shape specified in IEEE Std 501-1978. These tests were carried out in July of 1984. Response spectra computed from the base accelerometer outputs are shown in Figures 3 through 14. For the second phase, the controllers were re-adjusted to provide a higher overall level of shaking. These tests took place in December of 1984 and involved two cells - #57 which had previously taken part in a rack test, and #50 which had been tested in the single cell frame in July. Spectra from the second phase are shown in Figures 15 through 20.

The higher 'g' levels for the second stage tests were achieved largely by increasing the intensity of mid to high frequency components of the shaker motion (ie, above 5 Hz). The result is a spectrum shape that is rather higher than the standard IEEE 501 shape over the high frequency range. If such a spectrum is compared to the standard shape strictly according to the IEEE 501 methodology, then the ZPA of the fitted spectrum will be a very conservative estimate of the peak accelerations that the cell actually experienced. In this context, it must be recognized that the IEEE Standard is intended to provide a basis for the seismic qualification of a broad range of electrical equipment. The purpose of the experiments described here, however, is not to qualify the cells, but to explore the types of damage that might be inflicted by earthquake motion. Thus, we believe that we are justified in departing from the strict letter of the Standard so that the ZPA values quoted in our results are reasonably close to the peak accelerations encountered during the tests. (See Appendix A for a more complete discussion). To provide meaningful ZPA data, we have fitted an alternative set of normalized spectra to the experimental data over the 4 Hz to 33 Hz range. These alternative spectra are shown on Figures 15 through 20 as double lines.

2.3 Jar Fragility Test

Earlier testing (Gould NCX2250 cells from J.A. Fitzpatrick NPP/8/) had shown that cracks in the jars would propagate more readily if the cell was mounted loosely in the test frame. A single test was carried out with an LCU-13 cell loosely mounted in the frame. In this case, the cell jar had no sign of prior cracking and no damage occurred as a result of the test.

2.4 Multi Cell Rack Test

The single cell tests were designed to focus on failure modes of internal components. To examine the possible failure modes that would be encountered with normal in-plant mounting arrangements, a shaker test was carried out on a set of three cells mounted on a rack that resembled typical seismically qualified battery racks (see Figure 2). The test log and results are shown on Tables 2 and 3, while test spectra are shown in Figures 21 to 23. No failures occurred during the rack tests.

For practical reasons, the rack that was used for these tests held only three cells. Full scale racks in generating stations are typically much longer. The present tests could be non-conservative since long strings of cells could, under violent shaking, impose large impact loads on cells at the end of the string. These tests provide no positive indication that this is

a potential source of trouble. Nevertheless, we suggest that in severe seismic environments, it would be beneficial to separate cells into groups of three or so, with rigid partitions on the rack and flexible electrical connections between groups.

2.5 Post Seismic Capacity Tests and Inspection

Following the shaker table tests the cells were retested for electrical capacity. The results of these tests are shown on Table 1. For the first stage tests (ZPA around 1.5 g), there was some loss of discharge capacity for all cells. However, the cell capacities, as measured from the start of the seismic test series met the acceptance criterion of more than 80% rated capacity. For the second stage (ZPA around 2 g), the cells both provided uninterrupted power during the seismic tests, but had post-test capacities that were less than 80% of the rated capacity.

For the first stage seismic tests, the capacity tests were done within a few days of the shaker tests. In this case, the test capacity reflected the charge that remained in the cells after the shaking. However, the capacity tests that followed the second stage (higher intensity) seismic tests were delayed for approximately four weeks. Because of our experience with self-discharge of aged, seismically damaged cells, we believed that the charge remaining in the cells after this extended wait could be significantly lower than the charge that was available immediately following the shaker test. Accordingly, these two cells were recharged before the final capacity test. We do not know at this point how the extra discharge-charge cycle would effect the measured capacity.

Following the seismic tests, four of the cells were disassembled and inspected. It was found that the internal components were in good condition with very little plate growth, cracking or pitting and with only a modest amount of sediment.

3.0 CONCLUSIONS

1. The ten year old C&D LCU-13 cells that were the subject of this study were in good condition. They were all able to survive repeated strong shaking without sudden failure. There was apparently some loss of electrical capacity due to the seismic tests. All cells tested to the 1.5 g ZPA level passed the post-seismic capacity tests, but the two cells subjected to the 2 g ZPA tests showed capacity losses beyond the acceptance level for Class 1E battery cells.

2. Internal components of all of the cells that were disassembled appears to be in good condition with little plate swelling, cracking or pitting. There was only a modest amount of sediment.

3. There was no signs of damage to the jars during any of the tests. This includes test where a cell was free to move in and test frame (and hence would be subject to impact loads) and tests with multi-cell racks.

4.0 ACKNOWLEDGEMENTS

Test cells and funding for this project were provided by Sandia National Laboratories. This support is gratefully acknowledged. Lloyd Bonzon and Don Hente of SNL are thanked for their large contribution to the project. Within Ontario Hydro, contract coordination was handled by the Electrical Design Department. We are grateful to Colin Royce and Jerry Schendel for their efforts. Much of the testing and analysis was carried out by Brian Aucoin of the Chemical Research Department and Gordon Paulsen of the Mechanical Research Department. Their able work was essential to the successful outcome of the project.

Approved:

G.J. Clarke
Manager
Mechanical Research Dept

Submitted:

J.D. Tulk
Unit Head - Special Projects
Applied Structural and Solid Mechanics Section

D.A. Black
Engineer
Lines, Materials & Seismology

W.J. Janis
Chemist
Organic Section

C.J. Royce
Supervising Design Engineer - Studies and Analysis
Electrical Design Department
Design and Development Div

JDT/DAB/WJJ/CJR:ljh

REFERENCES

1. W.J. Janis, "Seismic Testing of North Anna Nuclear Power Station Batteries - Cell Inspection and Capacity Tests". Ontario Hydro Research Division Report C84-107-P.

2. J.A. Janis, "Seismic Testing of North Anna and Calvert Cliffs Nuclear Power Station Batteries - Second Stage; High Table Accelerations", Ontario Hydro Research Division Report C85-19-P.

3. D.A. Black and G.D. Paulson, "Seismic Testing of North Anna Nuclear Power Station Batteries (C&D LCU-13)". Ontario Hydro Research Division Report 84-419-P.

4. D.A. Black and G.D. Paulsen, "Seismic Retesting of North Anna Nuclear Power Station Batteries at Increased Accelerations", Ontario Hydro Research Division Report 85-55-P.

5. W.J. Janis, "Seismic Testing of Aged Nuclear Generating Station Batteries - Cell Inspection and Capacity Tests". Ontario Hydro Research Division Report C84-5-K.

6. G.D. Paulsen, "Seismic Qualification of Station Cells". Ontario Hydro Research Division Report B83-96-H.

7. D.A. Black and G.D. Paulsen. "Seismic Testing of Gould Cells Removed from Pickering GS in a Rack". Ontario Hydro Research Division Report B84-38-P.

8. J.D. Tulk, "D.A. Black, W.J. Janis and B.M. Kukreti, "Seismic Testing of Naturally Aged Station Battery Cells". NUREG/CR-3923 SAND 84-1737. (Also issued as Ontario Hydro Research Division Report B84-211-K).

9. J.D. Tulk, D.A. Black, W.J. Janis and B.M. Kukreti, "Seismic Testing of Naturally Aged Exide EMP-13 Station Battery Cells". Ontario Hydro Research Division Report 84-427-K.

10. J.D. Tulk, D.A. Black, W.J. Janis and B.M. Kukreti, "Seismic Testing of Naturally Aged Exide FHC-19 Station Battery Cells". Ontario Hydro Research Division Report 84-426-K.

11. IEEE Std 501-1978, "IEEE Standard, Seismic Testing of Relays", The Institute of Electrical and Electronics Engineers, Inc., 1978.

TABLE 1

CELL CAPACITIES BEFORE AND AFTER SEISMIC TESTING

First Stage Tests - ZPA Approximately 1.5 g

Cell	Time to 1.75 VPC at 3 h Rate Rate (min)			Percent of Rated Capacity at 3 h Rate		
	Pre-Seismic	Post-Seismic*	Post-Seismic Plus Seismic**	Pre-Seismic	Post Seismic*	Post-Seismic Plus Seismic**
6	184	165	176	102	92	98
7	206	190	198	114	106	110
36	206	145	156	114	81	87
46	181	160	168	101	89	93
48	187	155	161	104	86	89
50	192	160	168	107	89	93
57	192	165	176	107	92	98
AVG	193	163	172	107	91	95

Second Stage - ZPA Approximately 2 g

Cell	Time to 1.75 VPC at 3 h Rate Rate (min)		Percent of Rated Capacity at 3 h Rate	
	Pre-Seismic	Post-Seismic***	Pre-Seismic	Post Seismic***
50	162	120	89	67
57	164	56	91	31
AVG	163	88	90	49

* Cells not recharged following seismic testing (first stage)
** Capacity during seismic test at 1.0 h rate converted to 3 h capacity and added to post-seismic capacity, as discussed in Reference/1/.
*** Cells recharged following second stage seismic tests.

TABLE 2

TEST HISTORY - NORTH ANNA NPP - C & D - MODEL LCU-13

CELL	DATE	TIME	RUN	ZPA X/Y/Z	COMMENTS
Single Cell Tests					
7	July 24/84	1:14	1	0.6/0.5/0.6	
7	July 24/84	1:24	2	0.8/0.7/0.8	
7	July 24/84	1:25	3	0.9/0.9/1.0	
7	July 24/84	1:26	4	1.1/1.5/1.3	
7	July 24/84	1:27	5	1.3/1.9/1.5	Plotted
46	July 24/84	2:07	1	0.8/0.7/0.8	
46	July 24/84	2:27	2	0.8/0.7/0.8	
46	July 24/84	2:28	3	0.9/0.9/1.0	
46	July 24/84	2:29	4	1.1/1.5/1.3	
46	July 24/84	2:30	5	1.0/2.7/1.2	Plotted
50	July 24/84	3:00	1	0.8/0.7/0.8	
50	July 24/84	3:01	2	0.9/0.9/1.0	
50	July 24/84	3.02	3	1.1/1.5/1.3	
50	July 24/84	3:03	4	1.2/1.9/1.3	Plotted
50	July 24/84	3:07	5	1.3/1.9/1.5	Clamps Loose
48	July 25/84	9:39	1	0.8/0.9/0.8	
48	July 25/84	9:41	2	0.9/0.9/1.0	
48	July 25/84	9:42	3	1.1/1.5/1.3	
48	July 25/84	9:43	4	1.3/1.6/1.5	Plotted
57	Dec 10/84	9:25	1	1.4/1.2/1.6	
57	Dec 10/84	9:30	2	1.9/2.1/2.4	Plotted
50	Dec 10/84	10:12	1	1.4/1.2/1.6	
50	Dec 10/84	10:15	2	1.9/2.8/2.4	Plotted
Rack Test					
6,57,36	July 26/84	11:00	1	0.8/0.9/0.8	
6,57,36	July 26/84	11:03	2	0.9/0.9/1.0	
6,57,36	July 26/84	11:07	3	1.1/1.5/1.3	
6,57,36	July 26/84	11:09	4	1.1/1.9/1.3	Plotted

TABLE 3

SEISMIC TEST RESULTS

CELL NUMBER	DIRECTION	ZPA	FIGURE
Single Cell Tests - First Stage			
7	X	1.29	3
7	Y	1.88	4
7	Z	1.54	5
46	X	0.98	6
46	Y	2.74	7
46	Z	1.22	8
50	X	1.22	9
50	Y	1.89	10
50	Z	1.31	11
48	X	1.31	12
48	Y	1.56	13
48	Z	1.47	14
Single Cell Tests - Second Stage			
57	X	1.9	15
57	Y	2.1	16
57	Z	2.4	17
50	X	1.9	18
50	Y	2.8	19
50	Z	2.4	20
Rack Tests			
6,57,36	X	1.10	21
6,57,36	Y	1.92	22
6,57,36	Z	1.26	23

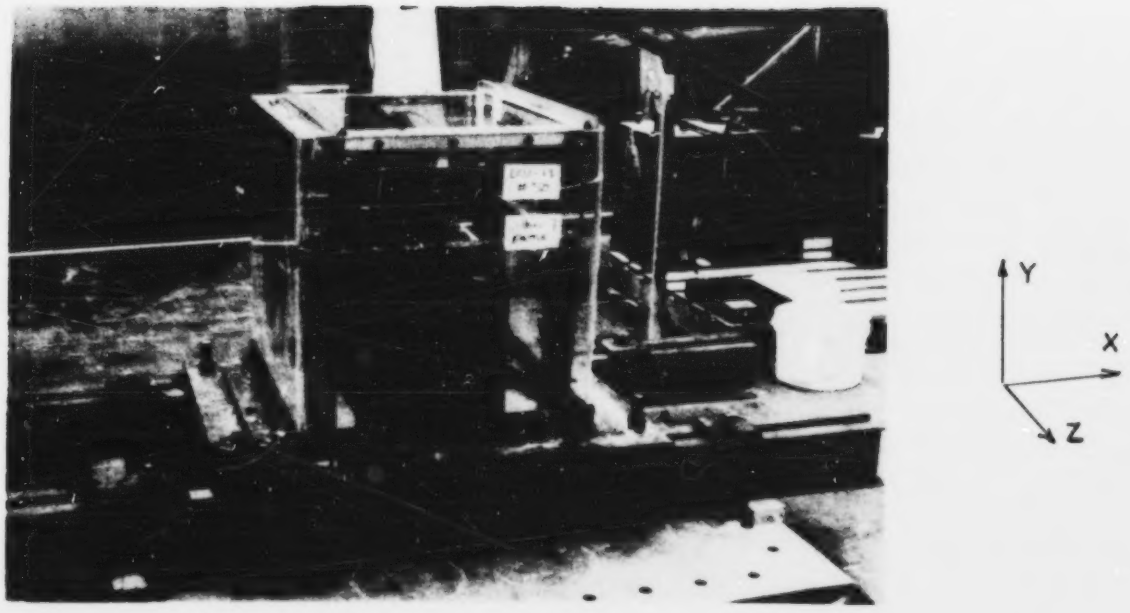


Figure 1

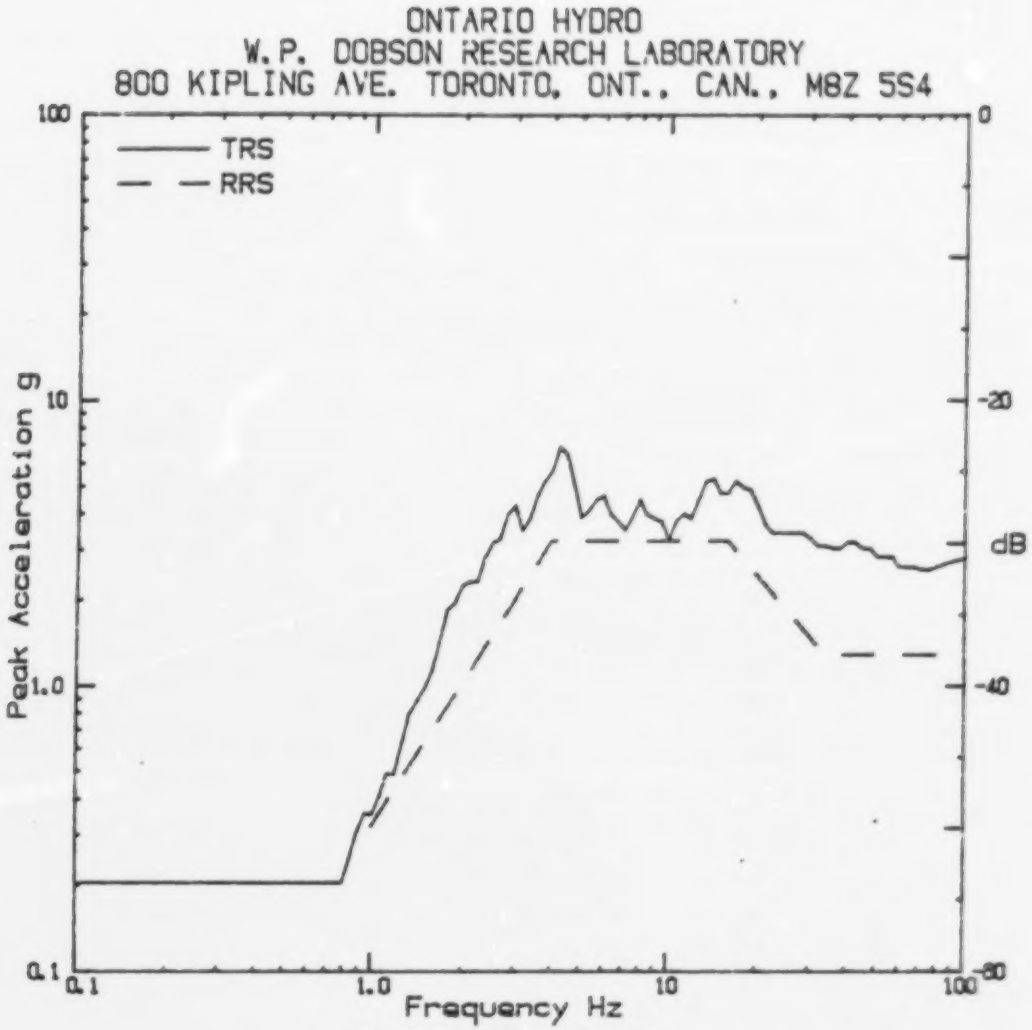
Typical mounting of a C&D LCU-13 cell in single-cell frame. Cell is clamped at four corners with threaded rods. Accelerometers are mounted on the base and on one of the terminal posts.

Axes of vibration are indicated.

Figure 2

Mounting of C&D LCU-13 cells in multi-cell rack.

Axes of vibration are indicated.



RESPONSE SPECTRUM

FIGURE 3

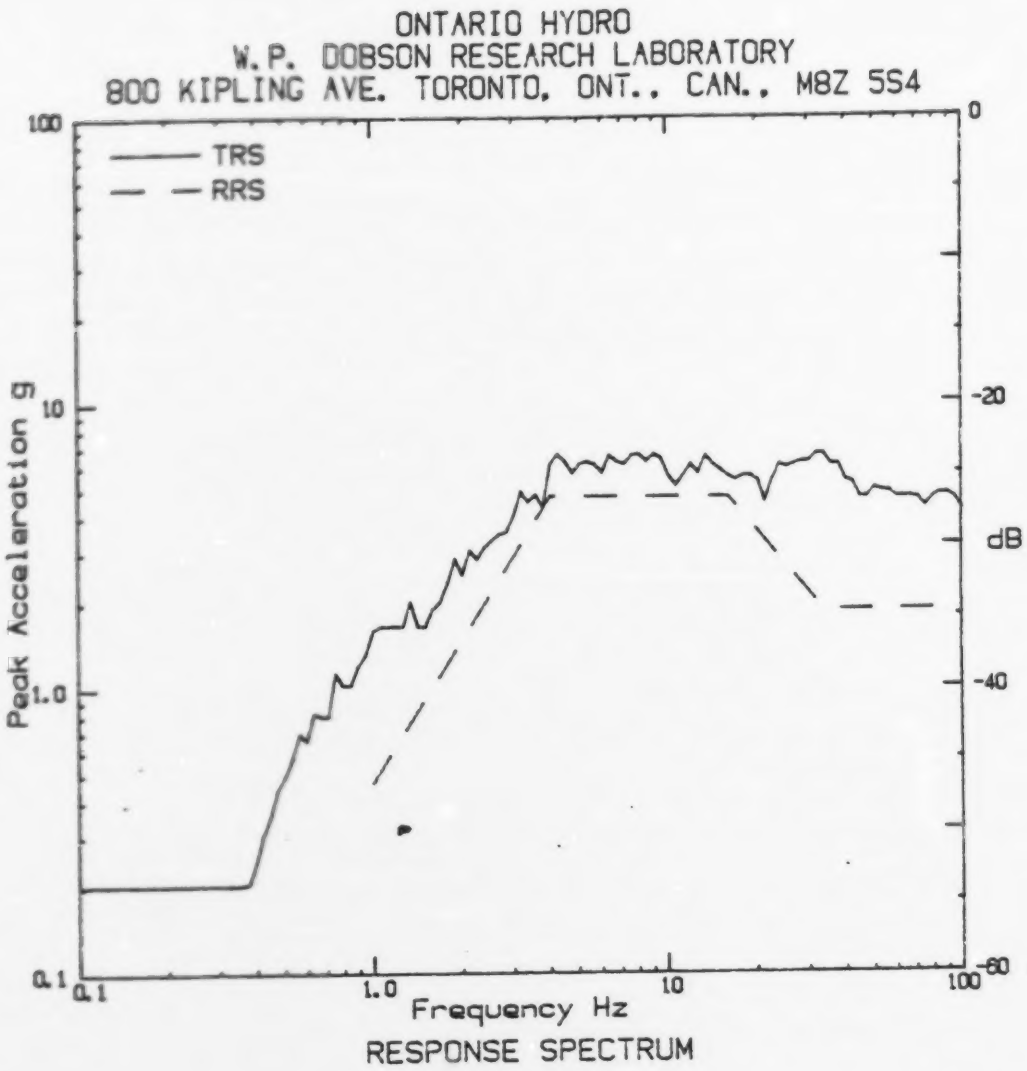
TEST ITEM
station cell. C&D Batteries. Model LCU-13. Serial 7

PARTICULARS
July 23/84. Time 1:28. Temp(°C) 23. Humidity(%) 53. Press (kPa) 100.2.
Graph 5224

SPECIFICATIONS
Spec IEEE 501. Conditions operating ; 3 hour rate. span 7

ANALYSIS
Type Maximax. Damping (%) 5. B.W. = 1/12 Octaves. Axis X.
Shaker tri-axial. ZPA=1.29g

ACCELEROMETER
Wilcoxon. Serial S771. Range dB49. Location base-mounting plate.
Channel 1F



RESPONSE SPECTRUM

FIGURE 4

TEST ITEM
station cell. C&D Batteries. Model LCU-13. Serial 7

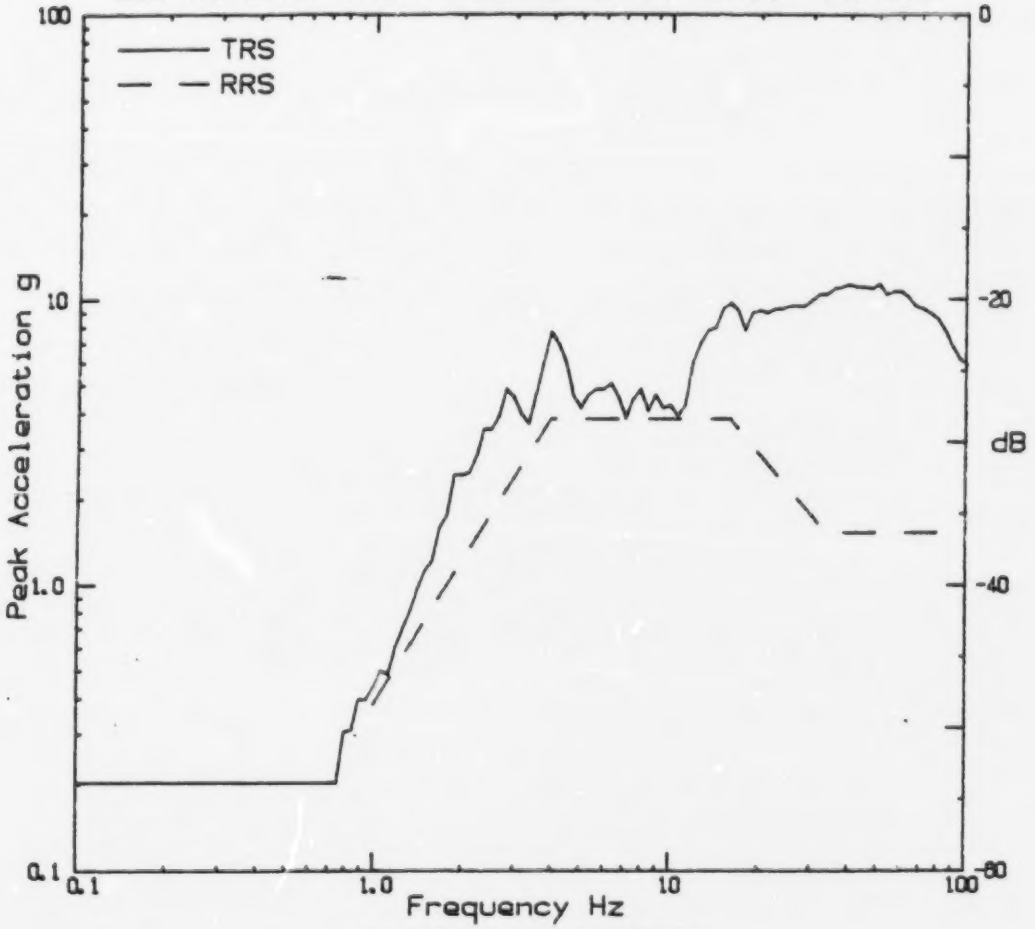
PARTICULARS
July 23/84. Time 1:28. Temp('C) 23. Humidity(%) 53. Press (kPa) 100.2.
Graph 5225

SPECIFICATIONS
Spec: IEEE 501. Conditions operating : 1 hour rate. span 7

ANALYSIS
Type Maximax. Damping (%) 5. B.W. = 1/12 Octaves. Axis Y.
Shaker tri-axial. ZPA=1.88g

ACCELEROMETER
Wilcoxon. Serial S761. Range dB49. Location base-mounting plate.
Channel 2

ONTARIO HYDRO
W. P. DOBSON RESEARCH LABORATORY
800 KIPLING AVE. TORONTO, ONT., CAN., M8Z 5S4



RESPONSE SPECTRUM

FIGURE 5

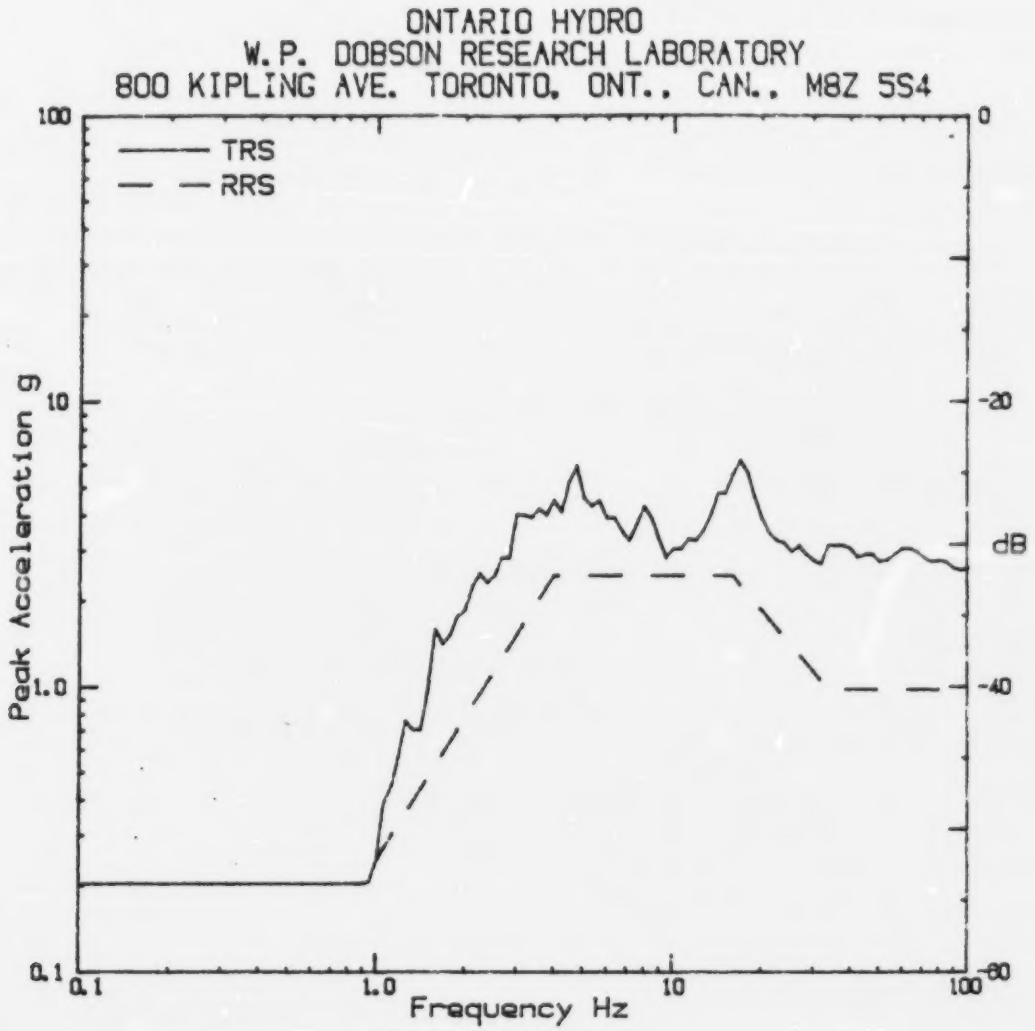
TEST ITEM
station cell, C&D Batteries, Model LCU-13, Serial 7

PARTICULARS
July 23/84, Time 1:28, Temp('C) 23, Humidity(%) 53, Press (kPa) 100.2.
Graph 5226

SPECIFICATIONS
Spec: IEEE 501, Conditions operating : 1 hour rate, span 7

ANALYSIS
Type Maximax, Damping (%) 5, B.W. = 1/12 Octaves, Axis Z.
Shaker tri-axial, ZPA=1.54g

ACCELEROMETER
Wilcoxon, Serial S297, Range dB49, Location base-mounting plate,
Channel 3



RESPONSE SPECTRUM

FIGURE 6

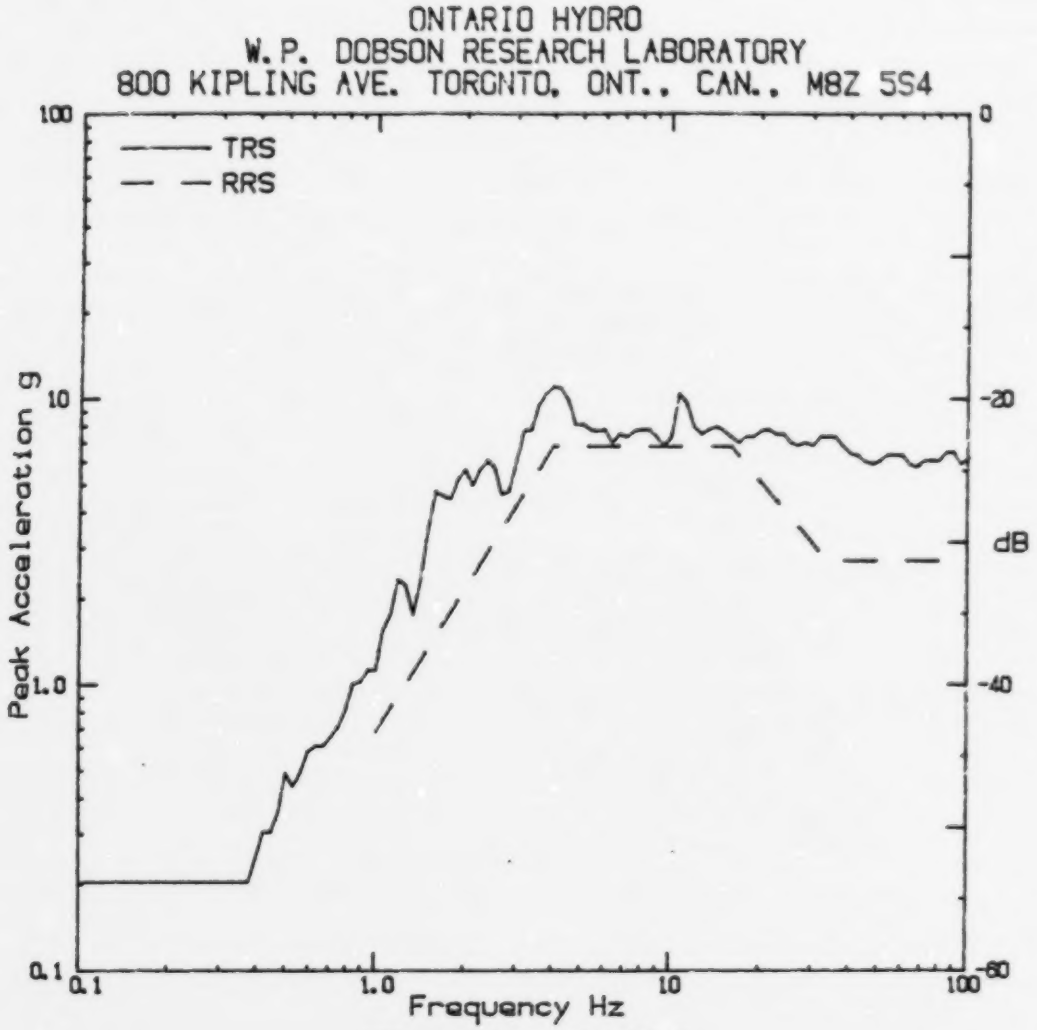
TEST ITEM
Station cells, C&D Batteries, Model LCU-13, Serial 46

PARTICULARS
July 23/84, Time 2:30, Temp('C) 23, Humidity(%) 53, Press (kPa) 100.2.
Graph 5230

SPECIFICATIONS
Specs IEEE 501, Conditions operating ; 1 hour rate, span 7

ANALYSIS
Type Maximax, Damping (%) 5, B.W. = 1/12 Octaves, Axis X.
Shaker tri-axial, ZPA=.98g

ACCELEROMETER
Wilcoxon, Serial S771, Range d949, Location base-mounting plate.
Channel 1



RESPONSE SPECTRUM

FIGURE 7

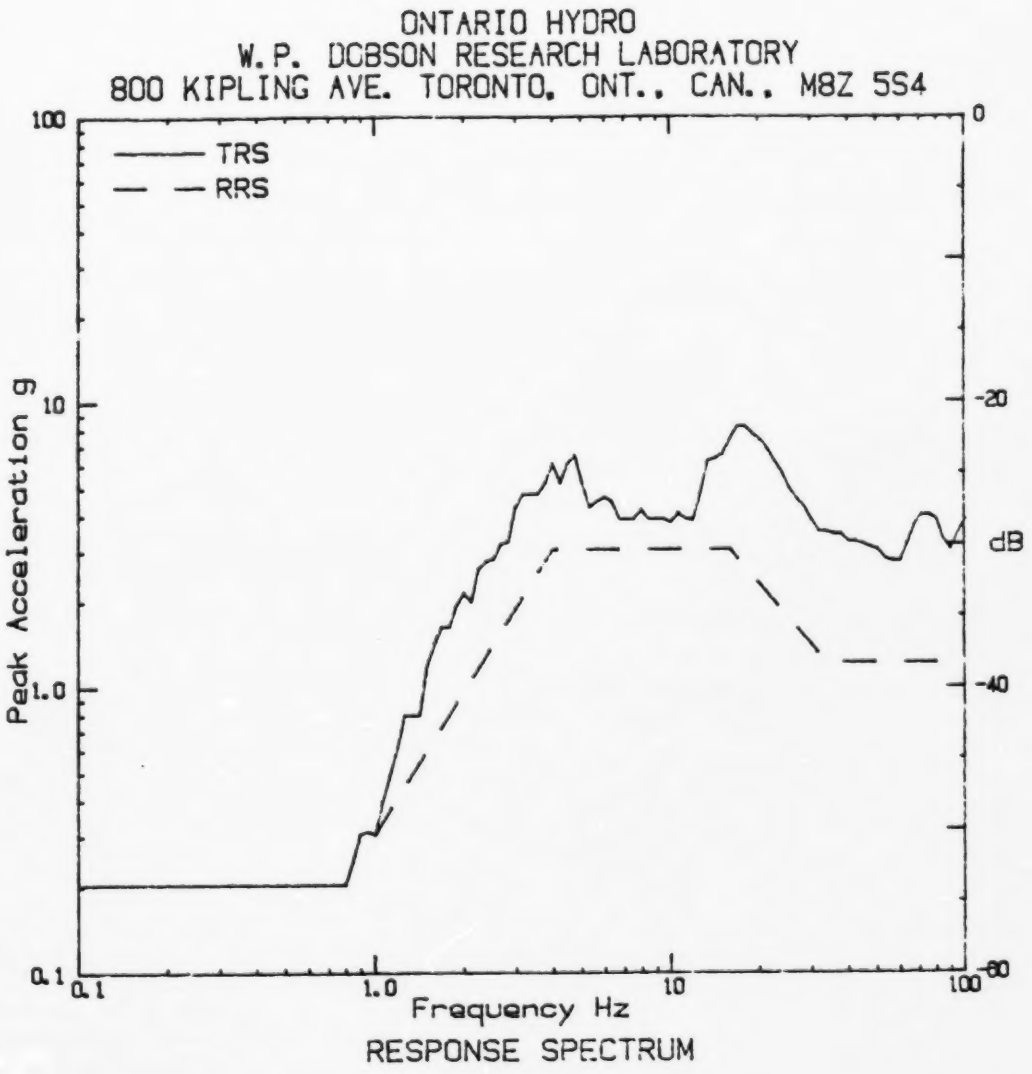
TEST ITEM
Station cells, C&D Batteries, Model LCU-13, Serial 46

PARTICULARS
July 23/84, Time 2:30, Temp('C) 23, Humidity(%) 53, Press (kPa) 100.2.
Graph 5231

SPECIFICATIONS
Spec: IEEE 501, Conditions operating ; 1 hour rate, span 7

ANALYSIS
Type Maximax, Damping (%) 5, B.W. = 1/12 Octaves, Axis Y.
Shaker tri-axial, ZPA=2.74g

ACCELEROMETER
Wilcoxon, Serial S761, Range dB49, Location base-mounting plate,
Channel 2



RESPONSE SPECTRUM

FIGURE 8

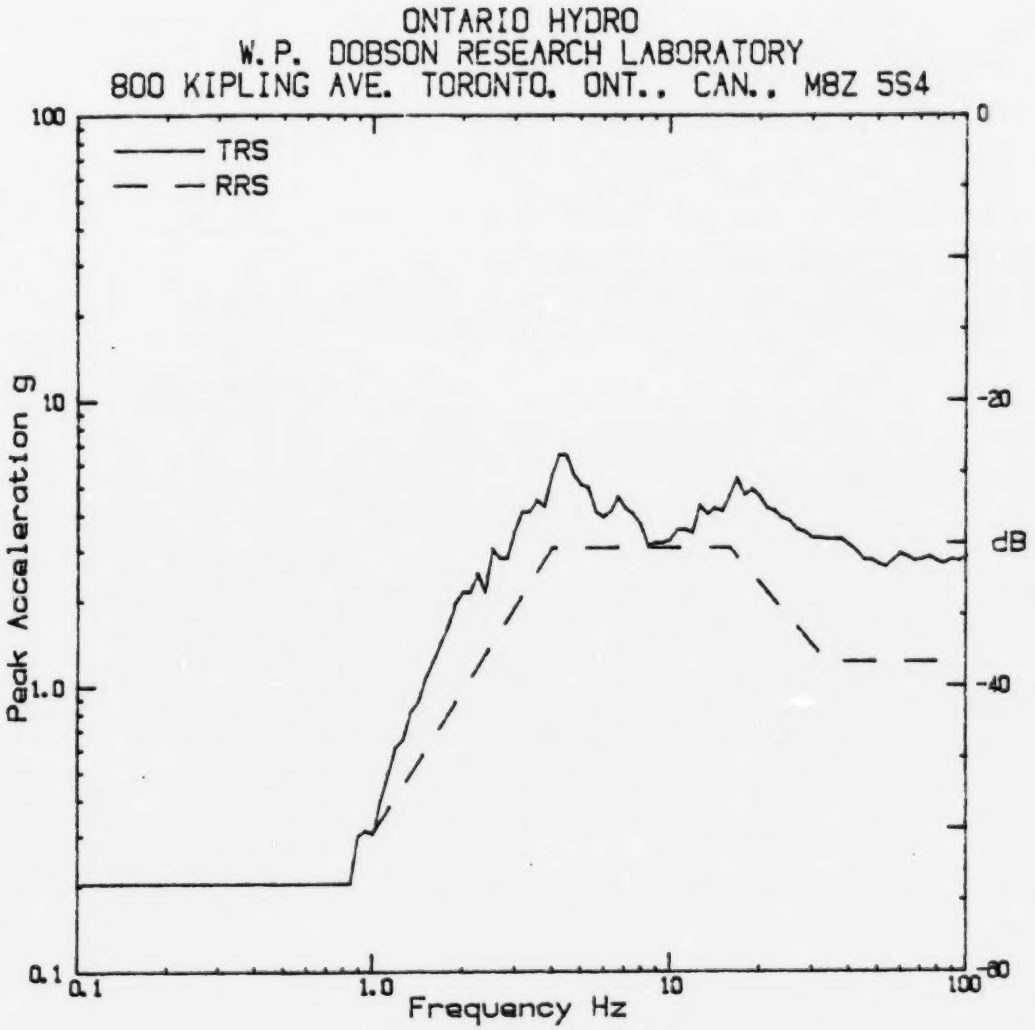
TEST ITEM
Station cells, C&D Batteries, Model LCU-13, Serial 46

PARTICULARS
July 23/84, Time 2:30, Temp(°C) 23, Humidity(%) 53, Press (kPa) 100.2,
Graph 5232

SPECIFICATIONS
Spec: IEEE 501, Conditions operating ; 1 hour rate, span 7

ANALYSIS
Type Maximax, Damping (%) 5, B.W. = 1/12 Octaves, Axis Z,
Shaker tri-axial, ZPA=1.22g

ACCELEROMETER
Wilcoxon, Serial S297, Range dB49, Location base-mounting plate,
Channel 3



RESPONSE SPECTRUM

FIGURE 9

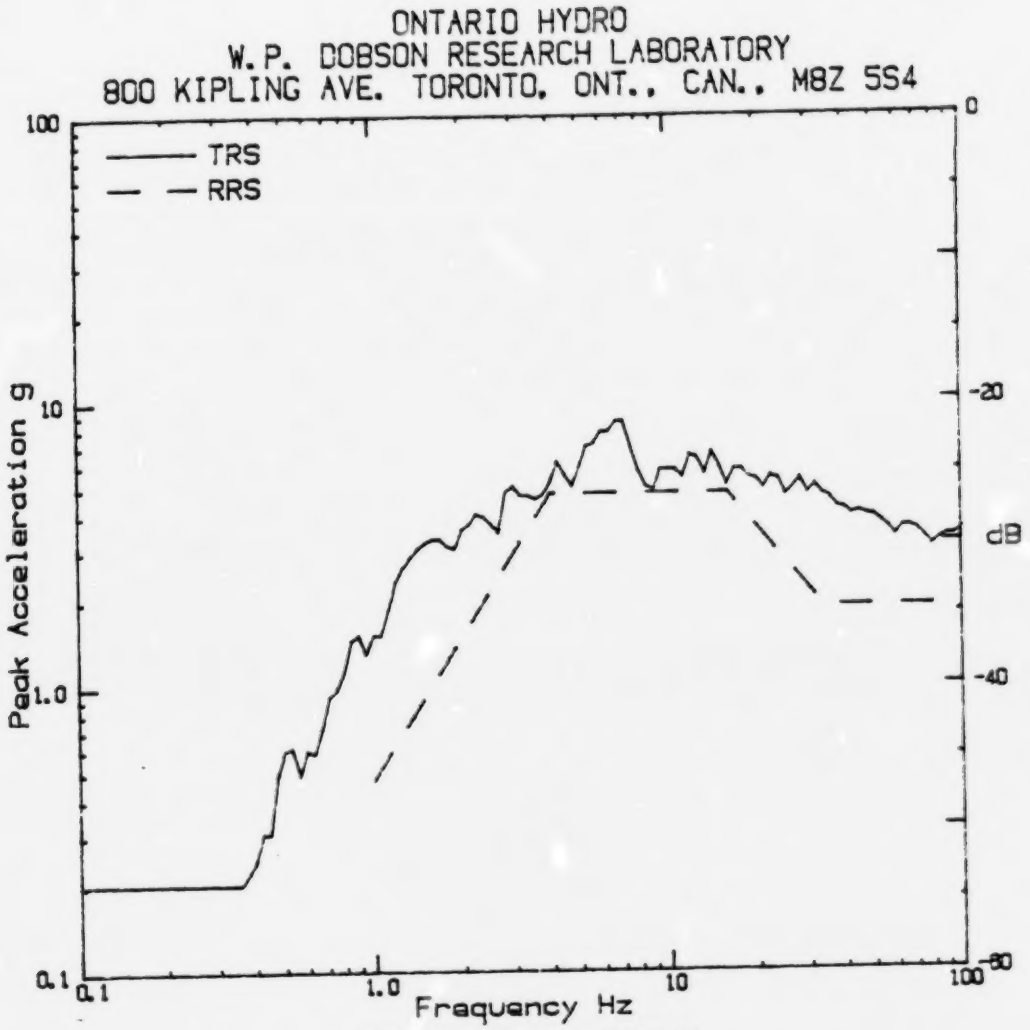
TEST ITEM
Station cells. C&D Batteries. Model LCU-13. Serial 50

PARTICULARS
July 23/84. Time 3:03. Temp('C) 23. Humidity(%) 53. Press (kPa)100.2.
Graph 5236

SPECIFICATIONS
Spece IEEE 501. Conditions operating ; 1 hour rate. span 7

ANALYSIS
Type Maximax. Damping (%)5. B.W.= 1/12 Octaves. Axis X.
Shaker tri-axial. ZPA=1.22g

ACCELEROMETER
Wilcoxon. Serial S771. Range dB49. Location base-mounting plate.
Channel 1



RESPONSE SPECTRUM

FIGURE 10

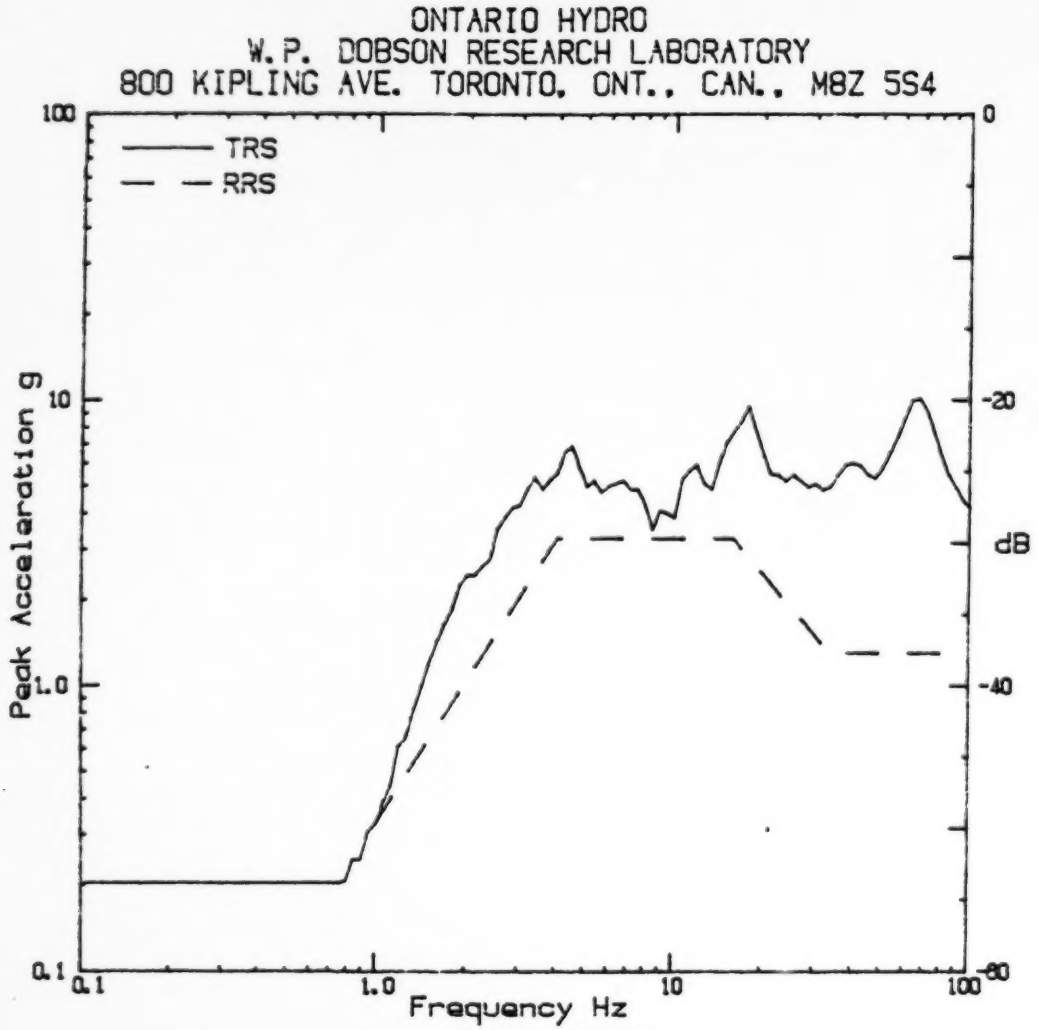
TEST ITEM
Station cells. C&D Batteries. Model LCU-13. Serial 50

PARTICULARS
Jwly 23/84. Time 3:03. Temp('C) 23. Humidity(%) 53. Press (kPa) 100.2.
Graph 5237

SPECIFICATIONS
Spece IEEE 501. Conditions operating : 1 hour rate. span 7

ANALYSIS
Type Maximax. Damping (%) 5. B.W.= 1/12 Octaves. Axis Y.
Shaker tri-axial. ZPA=1.89g

ACCELEROMETER
Wilcoxon. Serial S761. Range dB49. Location base-mounting plate.
Channel 2



RESPONSE SPECTRUM

FIGURE 11

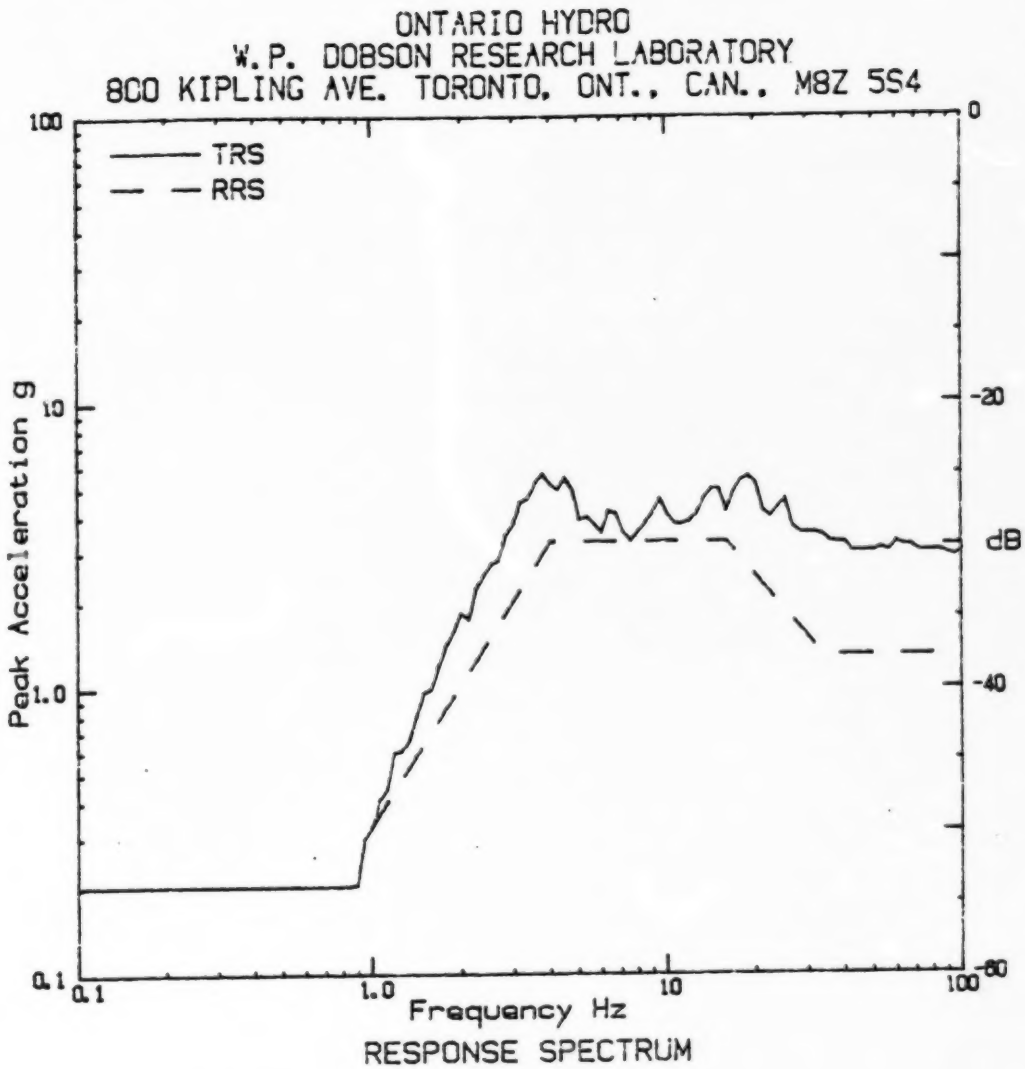
TEST ITEM
Station cells. C&D Batteries. Model LCU-13. Serial 50

PARTICULARS
July 23/84. Time 3:03. Temp('C) 23. Humidity(%) 53. Press (kPc) 100.2.
Graph 5238

SPECIFICATIONS
Specs IEEE 501. Conditions operating ; 1 hour rate. span 7

ANALYSIS
Type Maximax. Damping (%) 5. B.W. = 1/12 Octaves. Axis Z.
Shaker tri-axial. ZPA=1.31g

ACCELEROMETER
Wilcoxon. Serial S297. Range dB49. Location base-mounting plate.
Channel 3



RESPONSE SPECTRUM

FIGURE 12

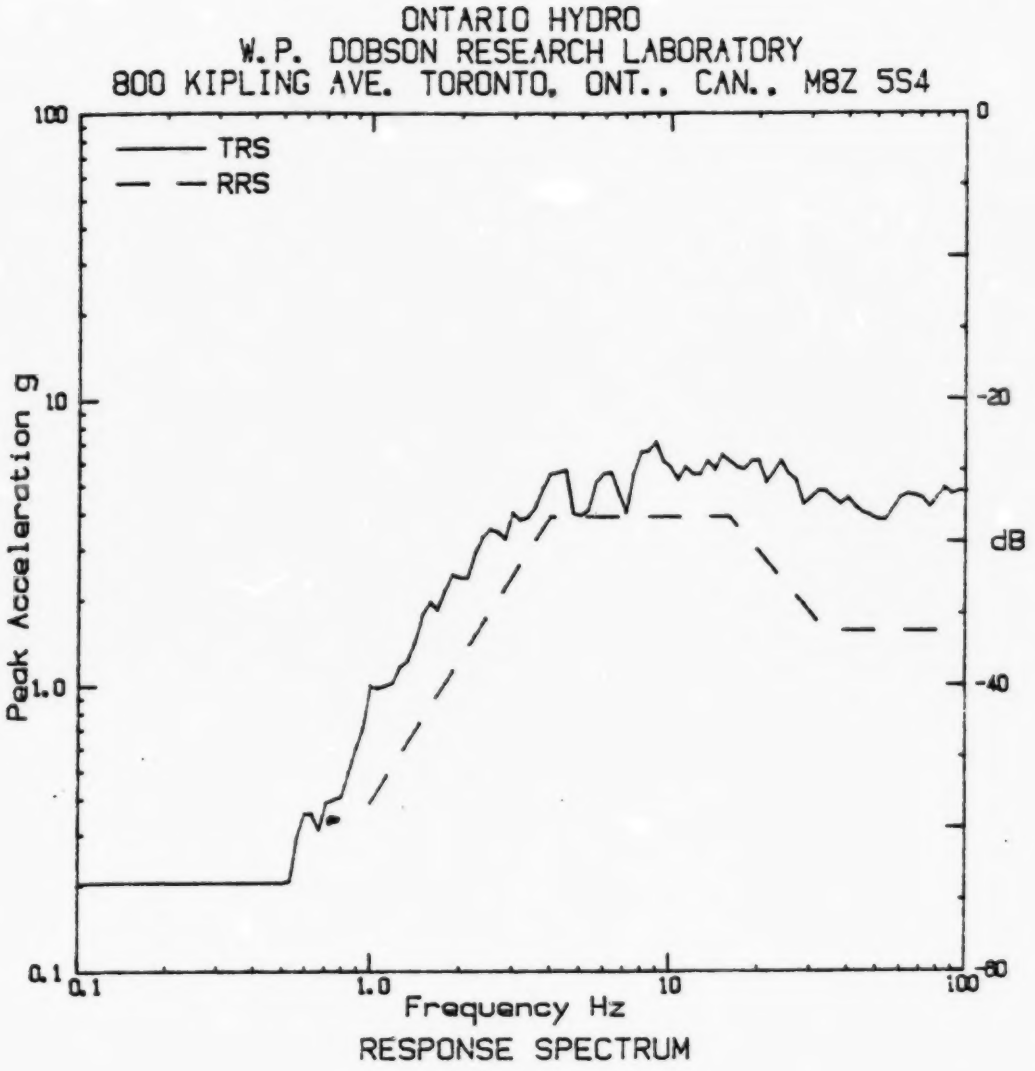
TEST ITEM
Station cells, C&D Batteries, Model LCU-13, Serial 48

PARTICULARS
July 24/84, Time 9:43, Temp('C) 23, Humidity(%) 55, Press (kPa) 100.3,
Graph 5242

SPECIFICATIONS
Specs IEEE 501, Conditions operating ; 1 hour rate, span 7

ANALYSIS
Type Maximax, Damping (%) 5, B.W. = 1/12 Octaves, Axis X,
Shaker tri-axial, ZPA=1.31g

ACCELEROMETER
Wilcoxon, Serial S771, Range d849, Location base-mounting plate,
Channel 1



RESPONSE SPECTRUM

FIGURE 13

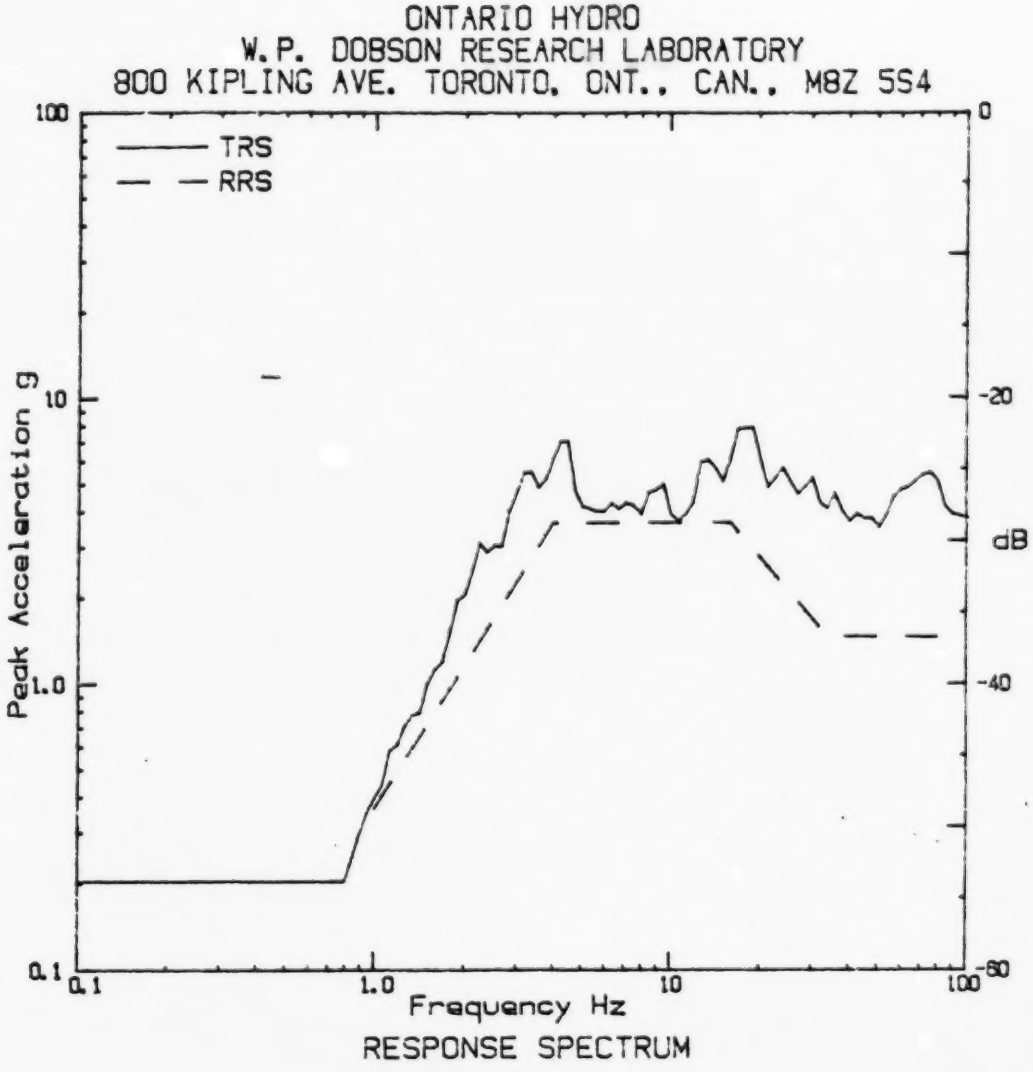
TEST ITEM
Station cells, C&D Batteries, Model LCU-13, Serial 48

PARTICULARS
July 24/84, Time 9:43, Temp('C) 23, Humidity(%) 55, Press (kPa) 100.3,
Graph 5243

SPECIFICATIONS
Specs IEEE 501, Conditions operating ; 1 hour rate, span 7

ANALYSIS
Type Maximax, Damping (%) 5, B.W. = 1/12 Octaves, Axis Y,
Shaker tri-axial, ZPA=1.56g

ACCELEROMETER
Wilcoxon, Serial S761, Range dB49, Location base-mounting plate,
Channel 2



RESPONSE SPECTRUM

FIGURE 14

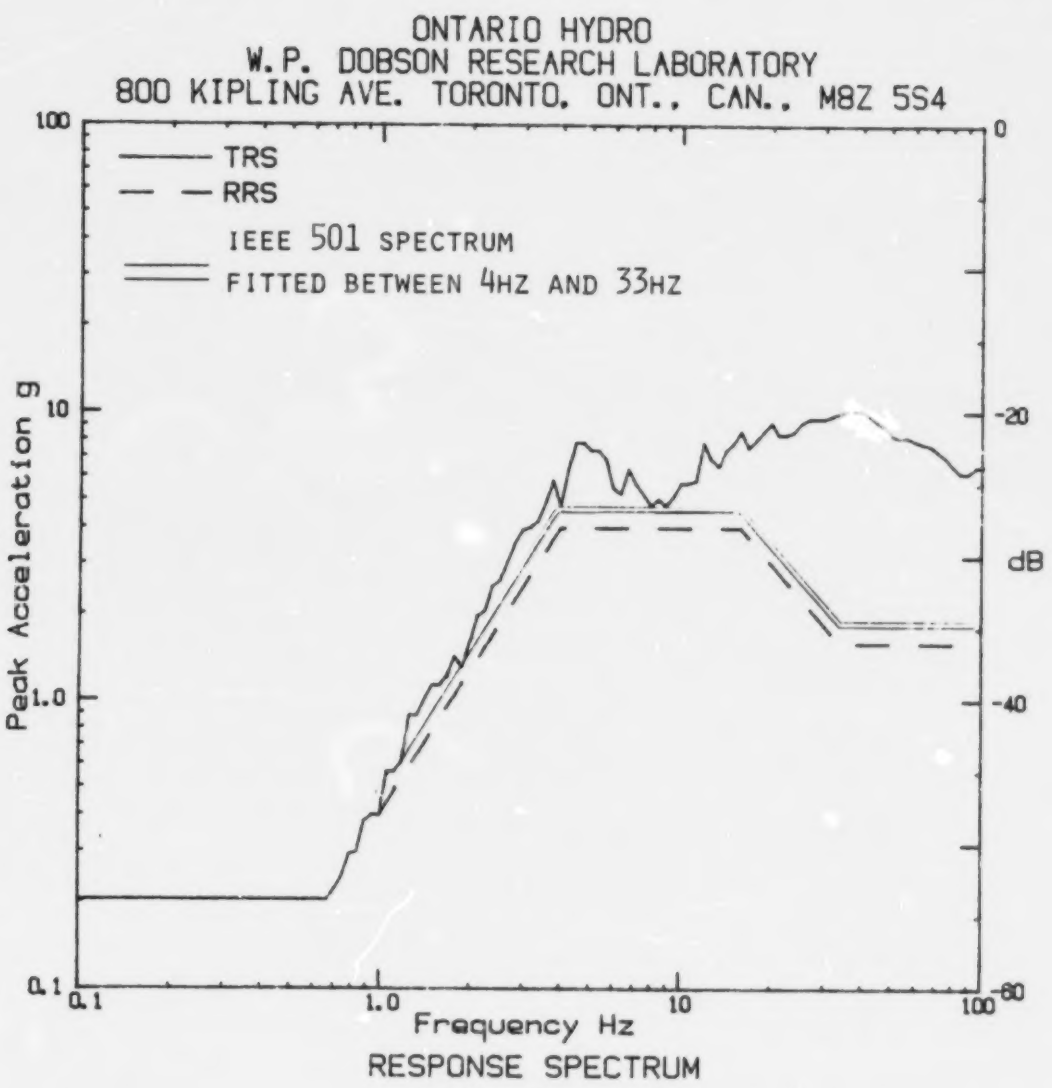
TEST ITEM
Station cells, C&D Batteries, Model LCU-13, Serial 48

PARTICULARS
July 24/84, Time 9:43, Temp('C) 23, Humidity(%) 55, Press (kPa) 100.3,
Graph 5244

SPECIFICATIONS
Spec IEEE 501, Conditions operating ; 1 hour rate, span 7

ANALYSIS
Type Maximax, Damping (%) 5, B.W. = 1/12 Octaves, Axis Z,
Shaker tri-axial, ZPA=1.47g

ACCELEROMETER
Wilcoxon, Serial S297, Range dB49, Location base-mounting plate,
Channel 3



RESPONSE SPECTRUM

FIGURE 15

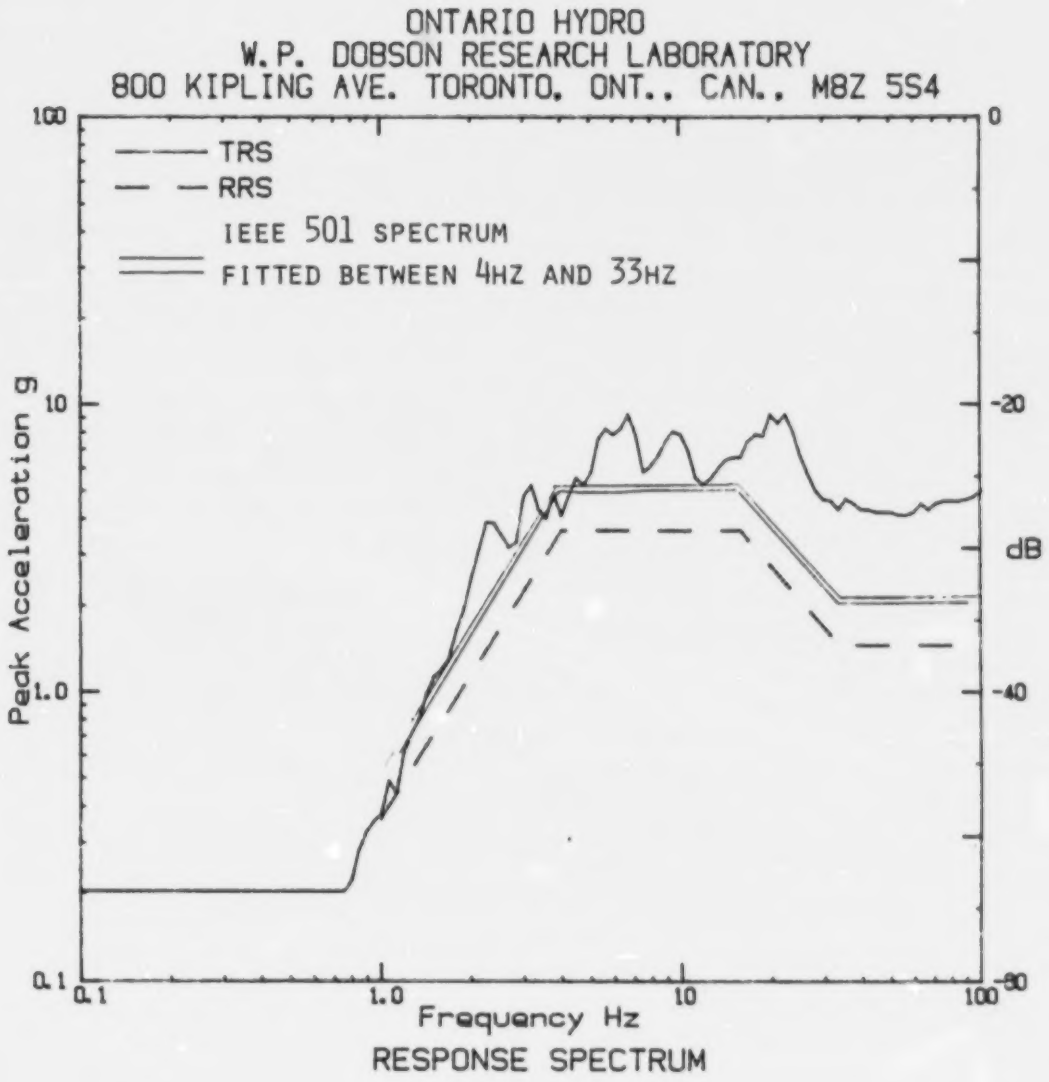
TEST ITEM
Station cell. C & D. Model LCU 13. cell #57

PARTICULARS
Dec 10/84. Time 9:30. Temp('C) 23. Humidity(%) 44. Press (kPa) 100.4.
Graph 5421

SPECIFICATIONS
Specs IEEE 344. Conditions operating. table limit

ANALYSIS
Type Maximax. Damping (%) 5. B.W. = 1/12 Octaves. Axis X.
Shaker tri-axial. ZPA=1.9 g

ACCELEROMETER
Wilcoxon. Serial 1214. Range dB48. Location base-mounting plate.
TT 733. Channel 1



RESPONSE SPECTRUM

FIGURE 16

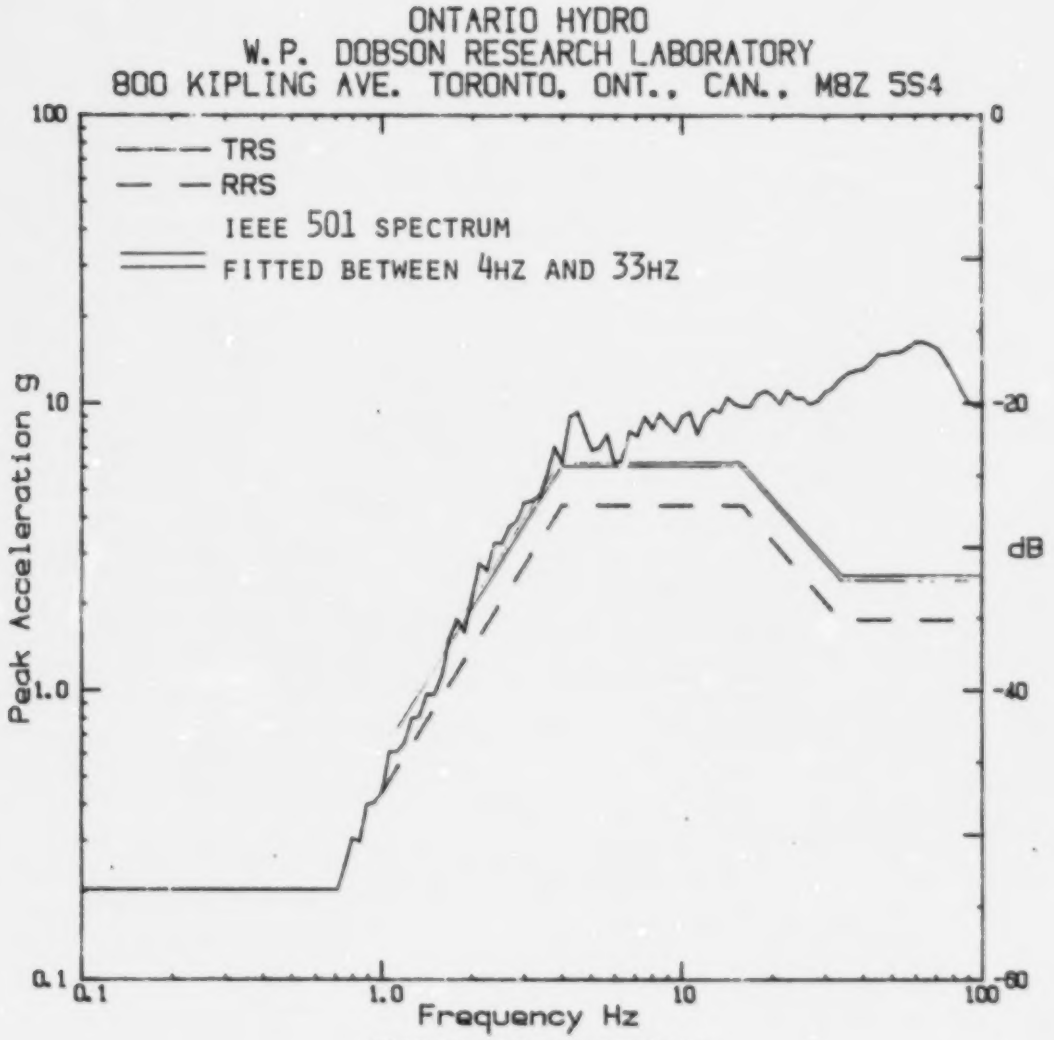
TEST ITEM
Station cell, C & D, Model LCU 13, cell #57

PARTICULARS
Dec 10/84, Time 9:30, Temp('C) 23, Humidity(%) 44, Press (kPa)100.4,
Graph 5422

SPECIFICATIONS
Specs IEEE 344, Conditions operating, table limit

ANALYSIS
Type Maximax, Damping (%)5, B.W. = 1/12 Octaves, Axis Y,
Shaker tri-axial, ZPA=2.1 g

ACCELEROMETER
Wilcoxon, Serial 1215, Range dB48, Location base-mounting plate,
TT 733, Channel 2



RESPONSE SPECTRUM

FIGURE 17

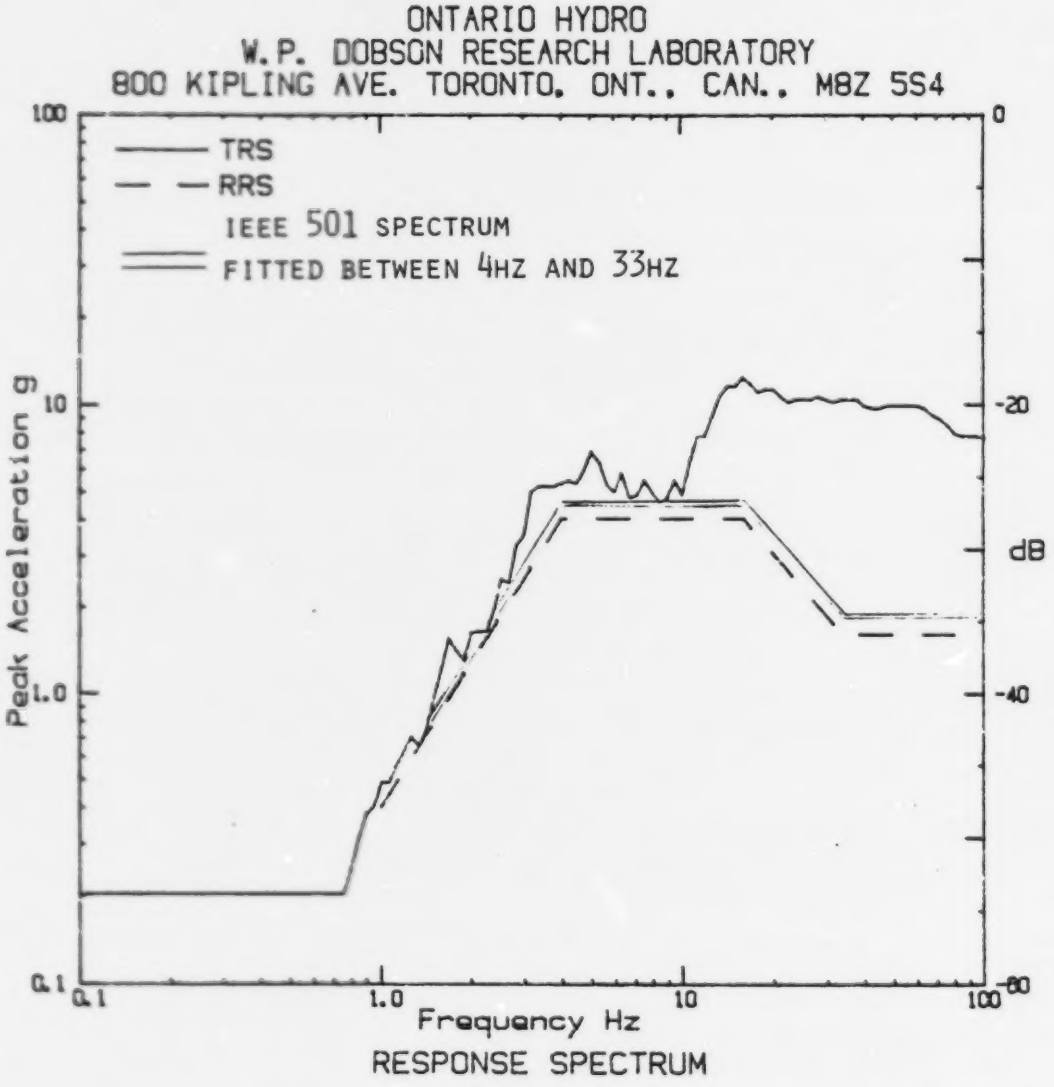
TEST ITEM
Station cell. C & D. Model LCU 13. cell #57

PARTICULARS
Dec 10/84. Time 9:30. Temp('C) 23. Humidity(%) 44. Press (kPa) 100.4.
Graph 5423

SPECIFICATIONS
Specs IEEE 344. Conditions operating. table limit

ANALYSIS
Type Maximax. Damping (%) 5. B.W. = 1/12 Octaves. Axis Z.
Shaker tri-axial. ZPA 2.4 g

ACCELEROMETER
Wilcoxon. Serial 1213. Range dB48. Location base-mounting plate.
TT 733. Channel 3



RESPONSE SPECTRUM

FIGURE 18

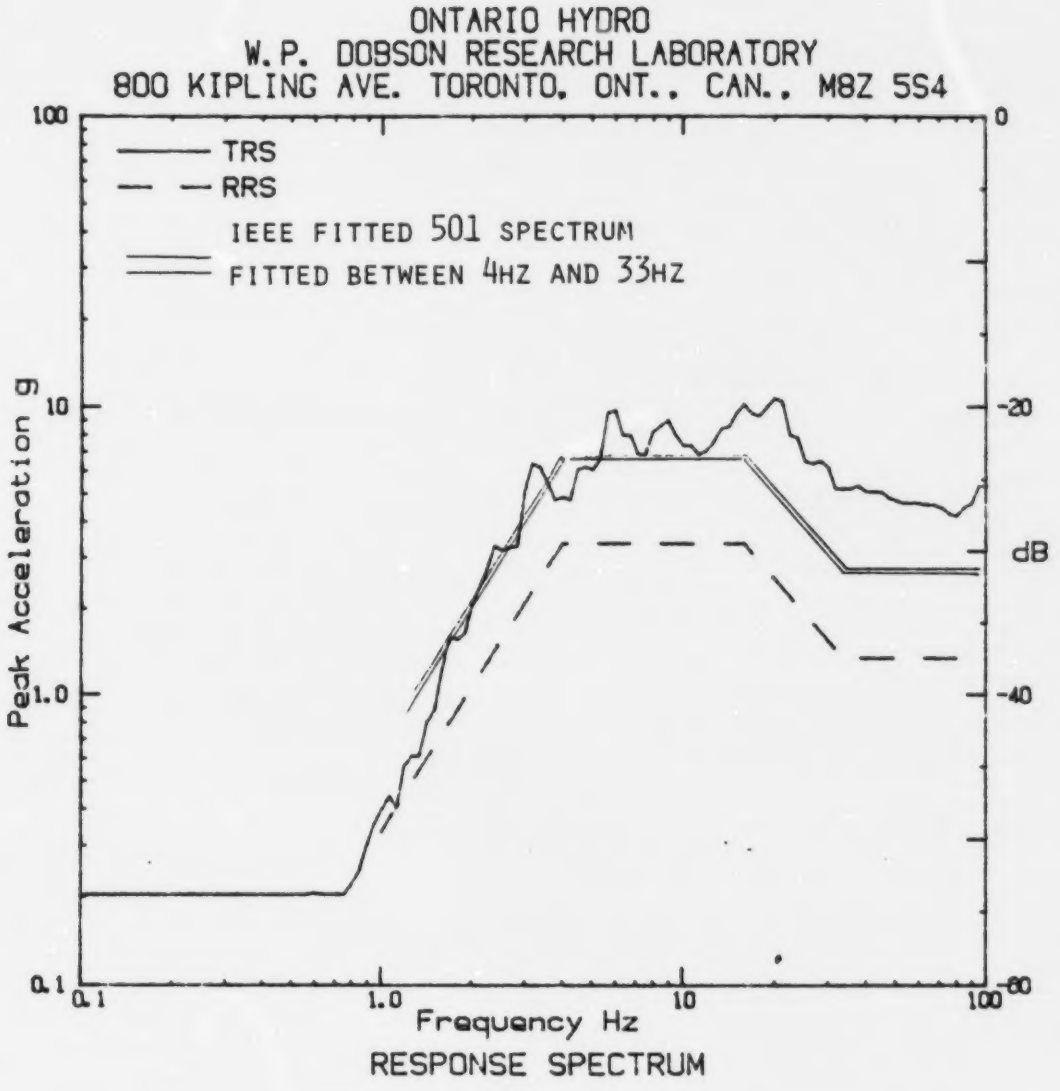
TEST ITEM
Station cell, C & D, Model LCU 13, cell #50

PARTICULARS
Dec 10/84, Time 10:15, Temp('C) 23, Humidity(%) 44, Press (kPa) 100.4,
Graph 5427

SPECIFICATIONS
Spec: IEEE 344, Conditions operating, table limit

ANALYSIS
Type Maximax, Damping (%) 5, B.W. = 1/12 Octaves, Axis X,
Shaker tri-axial, ZPA=1.9 g

ACCELEROMETER
Wilcoxon, Serial 1214, Range dB48, Location base-mounting plate,
TT 737, Channel 1



RESPONSE SPECTRUM

FIGURE 19

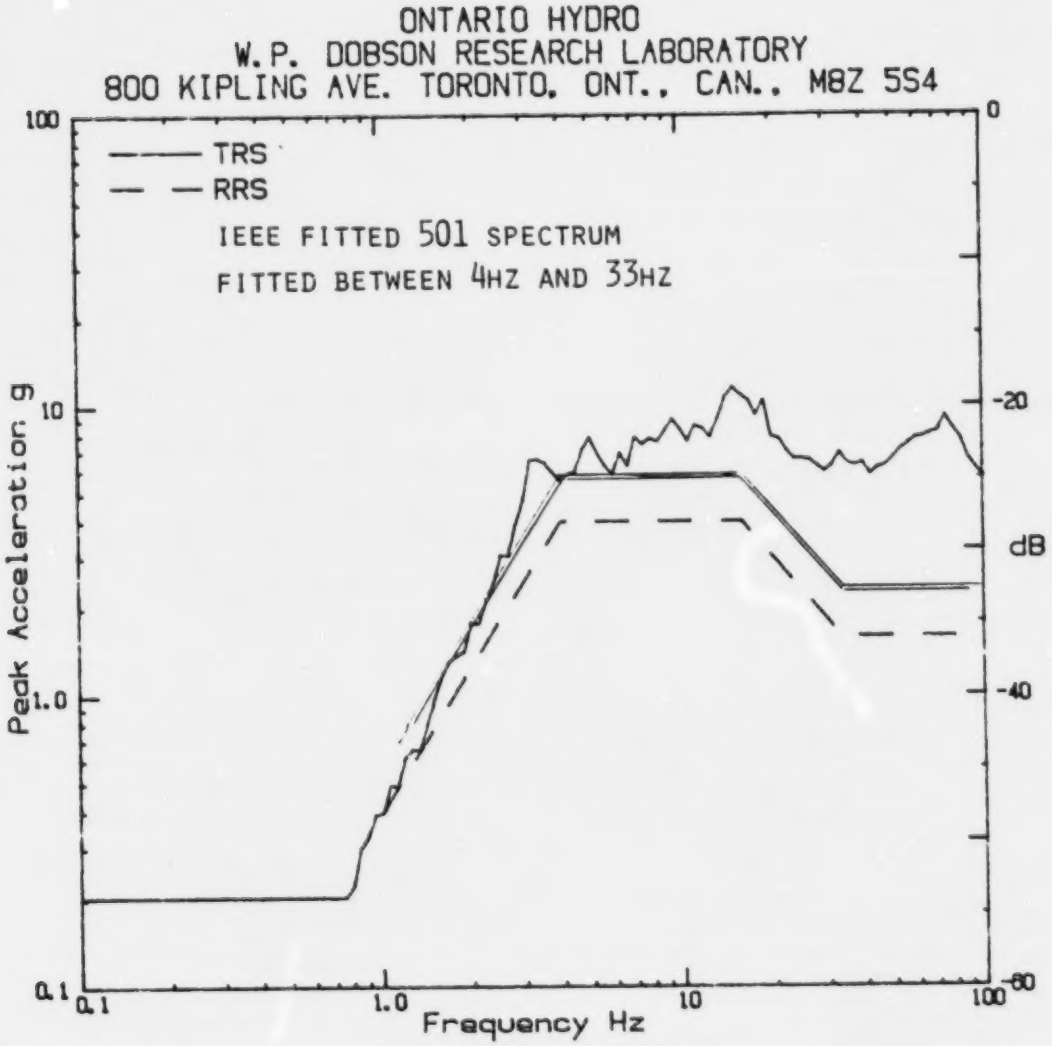
TEST ITEM
Station cell, C & D, Model LCU 13, cell #50

PARTICULARS
Dec 10/84, Time 10:15, Temp('C) 23, Humidity(%) 44, Press (kPa) 100.4,
Graph 5428

SPECIFICATIONS
Spec IEEE 344, Conditions operating, table limit

ANALYSIS
Type Maximax, Damping (%) 5, B.W. = 1/12 Octaves, Axis Y,
Shaker tri-axial, ZPA=2.8 g

ACCELEROMETER
Wilcoxon, Serial 1215, Range dB48, Location base-mounting plate,
TT 737, Channel 2



RESPONSE SPECTRUM

FIGURE 20

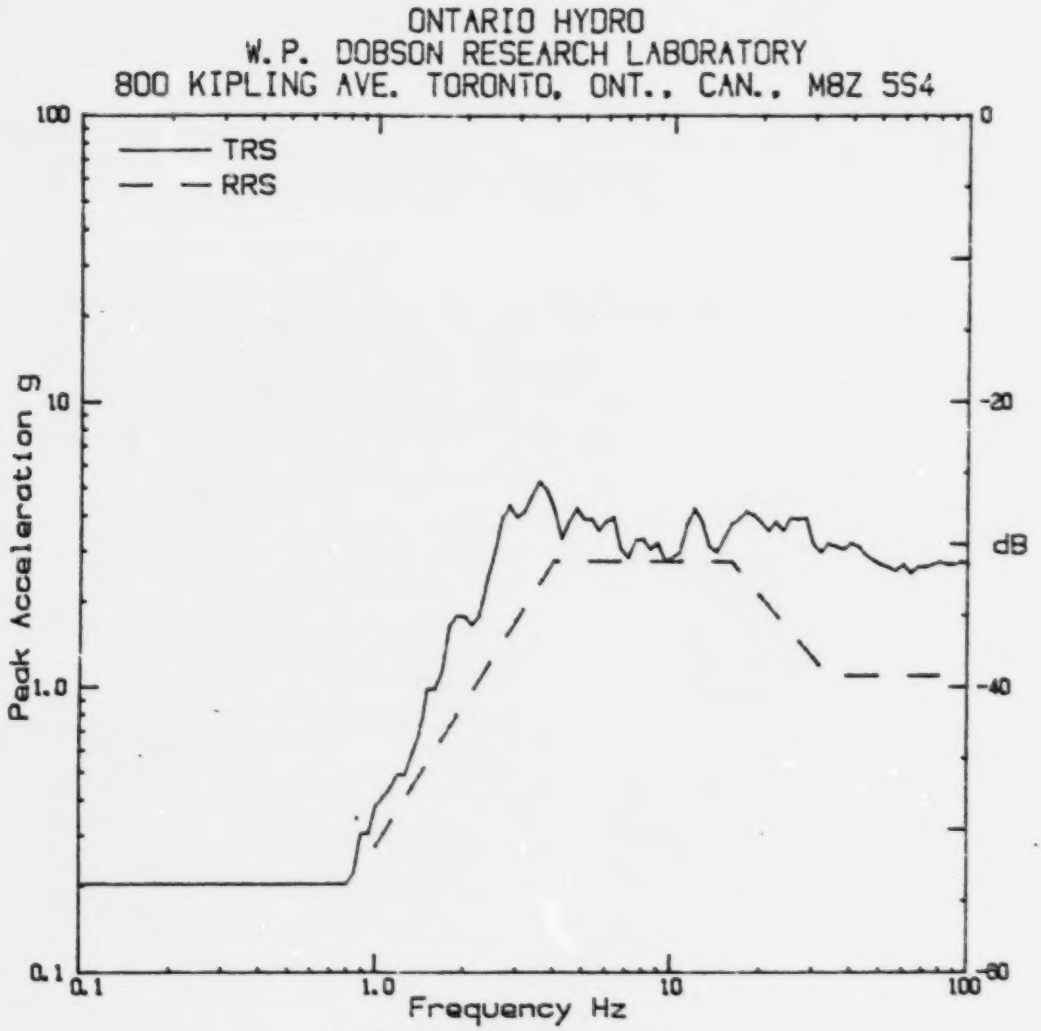
TEST ITEM
Station cell. C & D. Model LCU 13. cell #50

PARTICULARS
Dec 10/84. Time 10:15. Temp('C) 23. Humidity(%) 44. Press (kPa) 100.4.
Graph 5429

SPECIFICATIONS
Specs IEEE 344. Conditions operating. table limit

ANALYSIS
Type Maximax. Damping (%) 5. B.W. = 1/12 Octaves. Axis Z.
Shaker tri-axial. ZPA= 2·4g

ACCELEROMETER
Wilcoxon. Serial 1213. Range dB48. Location base-mounting plate.
TT 737. Channel 3



RESPONSE SPECTRUM

FIGURE 21

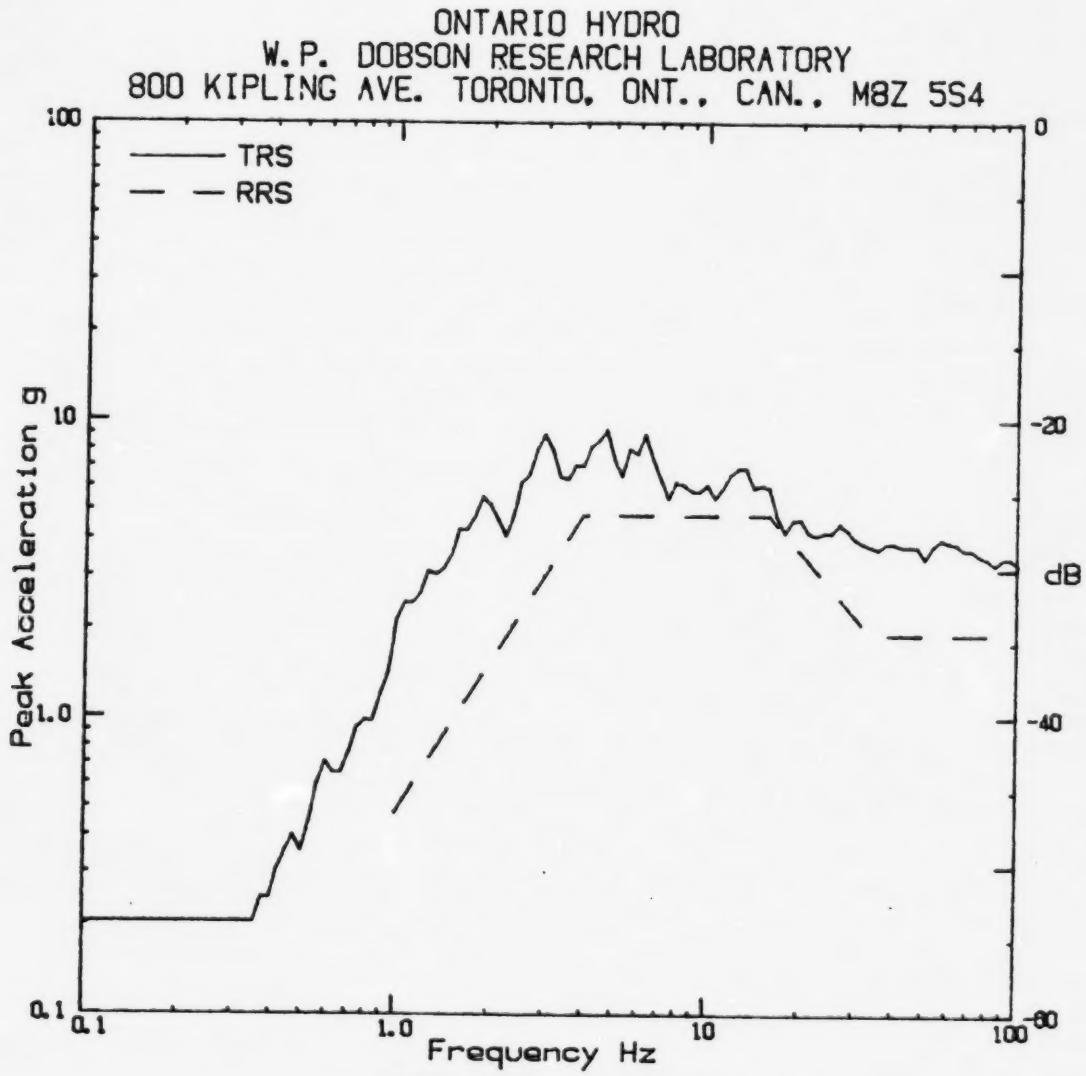
TEST ITEM
Station cells & Rack. C&D Batteries. Modal LCU-13. Serial 6.57.36

PARTICULARS
July 26/84. Time 11:09. Temp('C) 23. Humidity(%) 55. Press (kPa) 100.
Graph 5254

SPECIFICATIONS
Specs IEEE 501. Conditions operating ; 1 hour rate. span 7

ANALYSIS
Type Maximax. Damping (%) 5. B.W. = 1/12 Octaves. Axis X.
Shaker tri-axial. ZPA=1.1g

ACCELEROMETER
Wilcoxon. Serial S771. Range dB49. Location base-mounting plate.
Channel 1



RESPONSE SPECTRUM

FIGURE 22

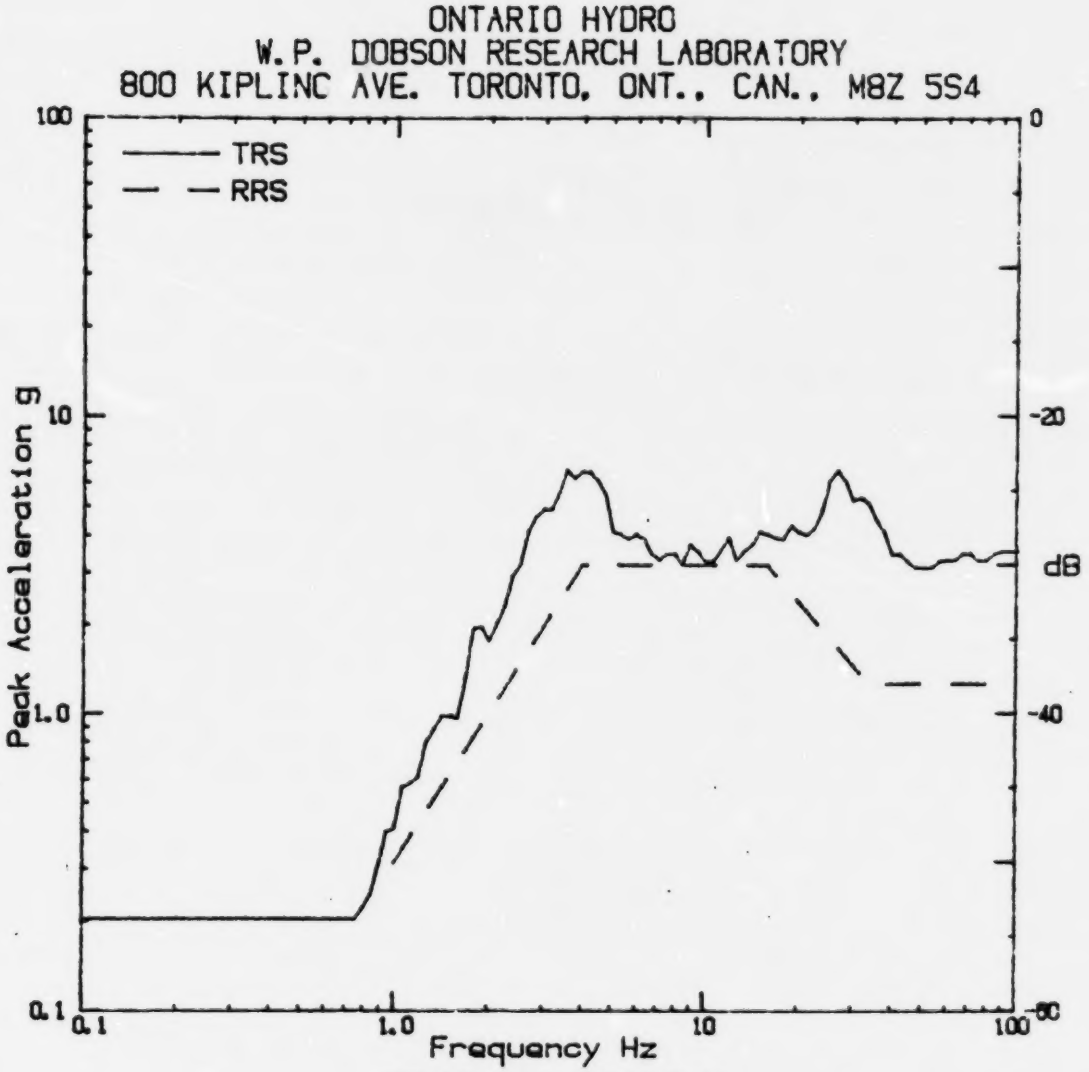
TEST ITEM
Station cells & Rack. C&D Batteries. Model LCU-13. Serial 6.57.36

PARTICULARS
July 26/84. Time 11:09. Temp('C) 23. Humidity(%) 55. Press (kPa) 100.
Graph 5255

SPECIFICATIONS
Specs IEEE 501. Conditions operating ; 1 hour rate. span 7

ANALYSIS
Type Maximax. Damping (%) 5. B.W. = 1/12 Octaves. Axis Y.
Shaker tri-axial. ZPA=1.92g

ACCELEROMETER
Wilcoxon. Serial S761. Range dB49. Location base-mounting plate.
Channel 2



RESPONSE SPECTRUM

FIGURE 23

TEST ITEM
Station calls & Rack, C&D Batteries, Model LCU-13, Serial 6,57,38

PARTICULARS
July 26/84, Time 11:09, Temp('C) 23, Humidity(%) 55, Press (kPa) 100,
Graph 5258

SPECIFICATIONS
Spece IEEE 501, Conditions operating ; 1 hour rate, span 7

ANALYSIS
Type Maximax, Damping (%) 5, B.W. = 1/12 Octaves, Axis Z,
Shaker tri-axial, ZPA=1.26g

ACCELEROMETER
Wilcoxon, Serial S297, Range dB48, Location base-mounting plate,
Channel 3

APPENDIX A

EARTHQUAKE MOTION AND RESPONSE SPECTRA

The way that a piece of equipment or structure responds to an earthquake will depend on the intensity of the event, and on the relationship between frequency content of the earthquake and the natural frequencies of the structure.

A convenient way of expressing the combination of intensity and frequency content of an earthquake is through the use of a graph known as a response spectrum. A response spectrum is made up by calculating the response level (acceleration, velocity or displacement) of a family of hypothetical single degree-of-freedom mechanical oscillators to the earthquake motion, and plotting these against frequency. A particular seismic "environment" is described by a set of spectra that define the response for different directions and levels of structural damping. The response of a simple structure to an earthquake can be estimated from the level of the appropriate spectra at the natural frequencies of the structure.

Response spectra deal with the response of structures to earthquake motion and contain no explicit information on the peak accelerations. However, it is known that earthquake motions is predominantly in the low frequency range (1-10 Hz) and that there will be relatively little amplification of the response of high frequency oscillators. Thus, for typical earthquake time-histories, the peak acceleration response for the oscillators at the high end of the frequency range will be quite close to the peak acceleration of the base motion from which the spectrum was generated. High frequencies correspond to short vibration periods and, in the jargon of the trade, the acceleration response at the high frequency end of the spectrum (33 Hz or above) is known as the Zero-Period Acceleration (ZPA). The ZPA is commonly taken as being equivalent to the peak acceleration of the seismic motion.

Response spectra are commonly used to define the seismic environments for structures or equipment that must survive earthquakes. Unless there is a large amount of site-specific data available, the spectra specified for a particular project are normally based on standard curves that have been developed to represent a broad range of possible conditions. The spectral curve defined in IEEE 501/11/ is typical. This standard specifies the relative intensity of the spectrum over the frequency range. The absolute intensity will depend on site conditions. For convenience, the absolute intensity is expressed as the ZPA.

When a particular piece of equipment is seismically qualified to IEEE 501, the test response spectra (ie, the response spectra calculated from the test motions) will be compared to the standard shape. The qualified level is the ZPA of the normalized curve that lies just below the test spectrum over the seismic frequency range (1-33 Hz).

For an efficient test, the test spectrum should closely match the standard spectral shape. However, in practical testing, the experimental curve will often "overshoot" the desired curve over certain frequency ranges. This may be because of mechanical limitations in the test rig. For example, the shaker table used in this series of tests has a limited stroke (displacement) so that it is difficult to generate very high response levels at low frequencies. Thus, when the rig is run at high power levels, the test motions often produce response spectra which are high in the high frequency range (above 5 Hz) and low at low frequencies, relative to the standard IEEE 501 shape. When these test spectra are fitted to the standard shape by strict rule, the result is a considerable overshot for much of the high frequency range. This means that the ZPA taken from the standard curve is far below the peak accelerations that were actually encountered.

As mentioned above, the standard shape was developed to represent a broad range of seismic conditions, structural supports and equipment types. The curves include a high level of response at low frequencies so that equipment with low natural frequencies will be adequately tested. However, in the case of the battery cells and racks, all of the structural modes of vibration have been found to have relatively high natural frequencies. This means that these devices will not be significantly effected by the low frequency component of the input motion. We believe that it is reasonable in this case to ignore the low frequency end of the experimental spectra and to fit the standard shape over a frequency range of 4-33 Hz. This has the effect of increasing the ZPA of the standard curve to a value that more accurately reflects the maximum accelerations encountered in each test.